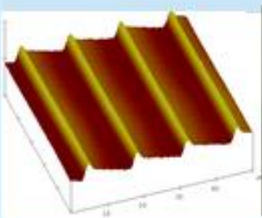
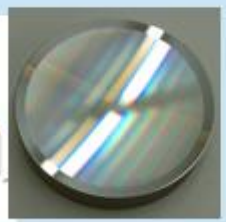
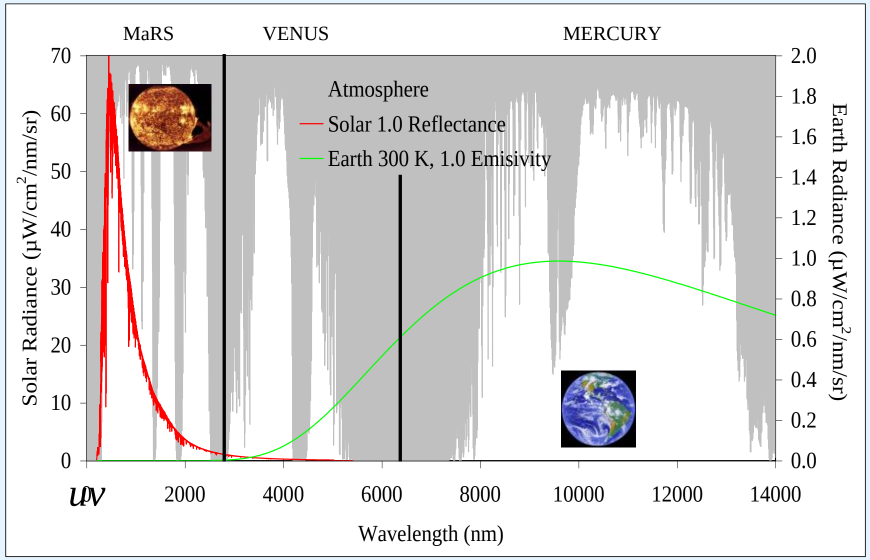
Imaging Spectrometer Design for high data fidelity

Design and Technology

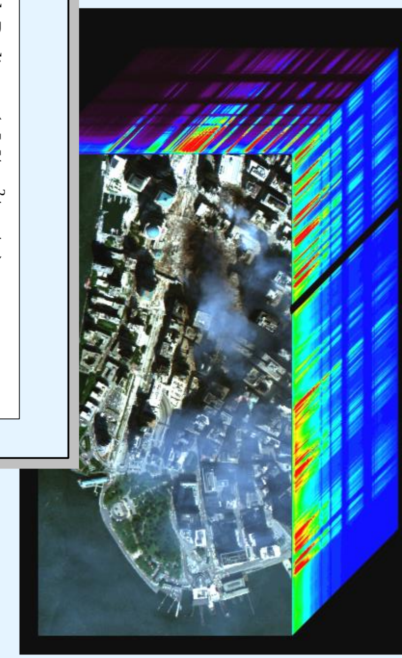




Optical Spectrum



Results

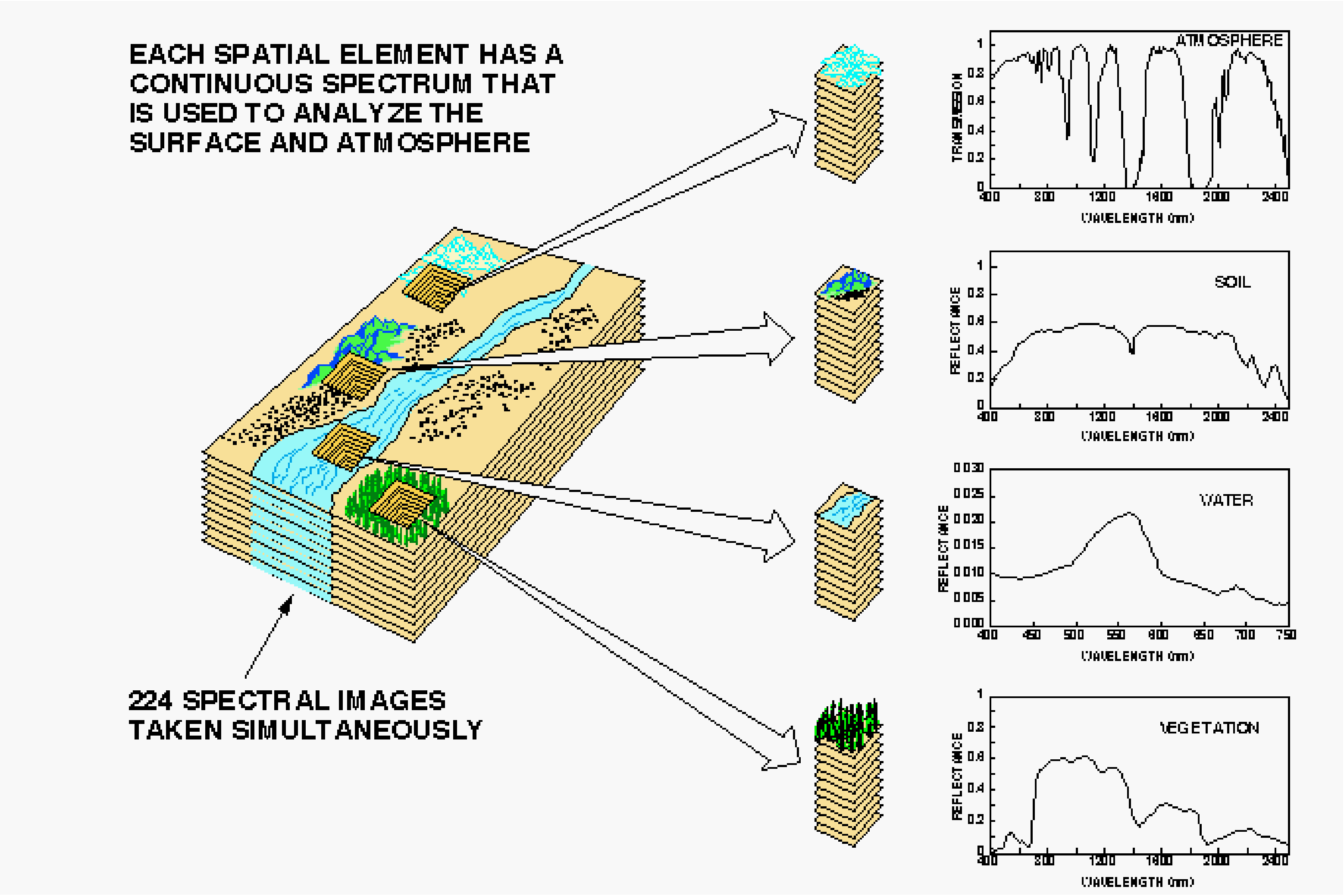


AVIRIS Assessment of Asbestos, Fires, and Debris World Trade Center September 16, 2001

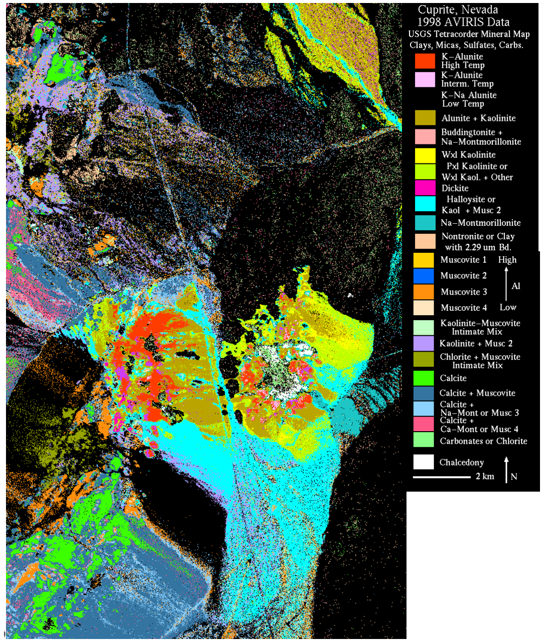
Pantazis Mouroulis

Jet Propulsion Laboratory, California Institute of Technology

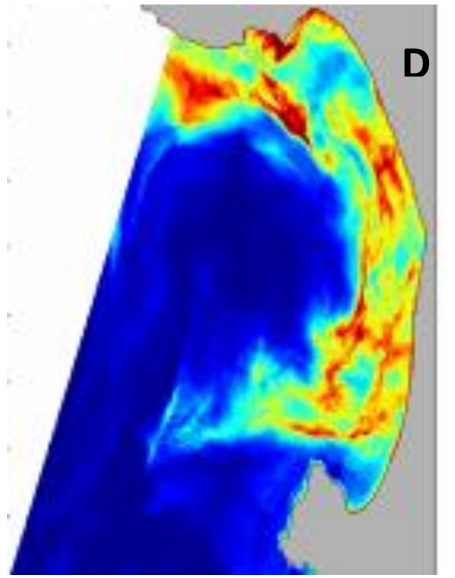
Imaging Spectroscopy



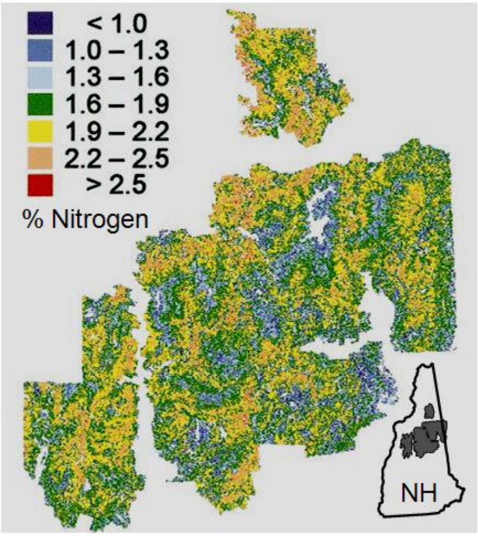
Imaging spectroscopy reveals the composition and condition of the Earth's surface



Material identification



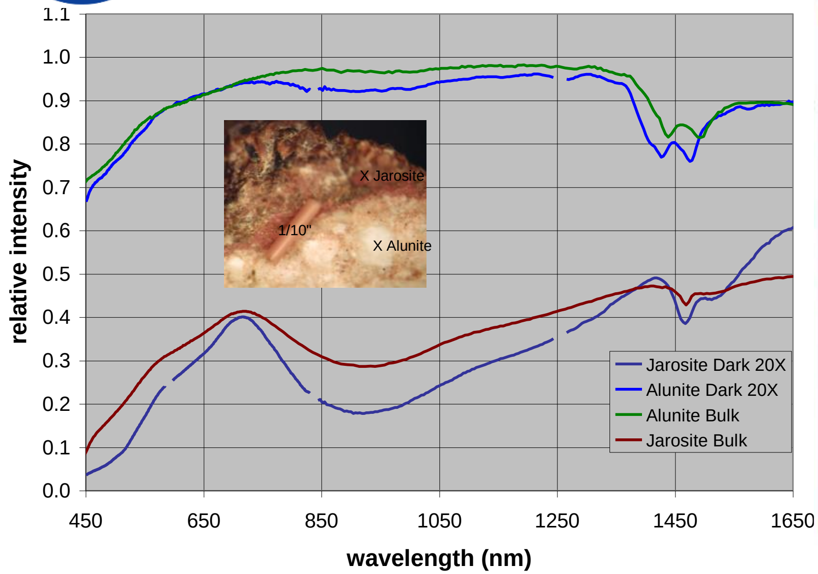
Hazards and episodic events



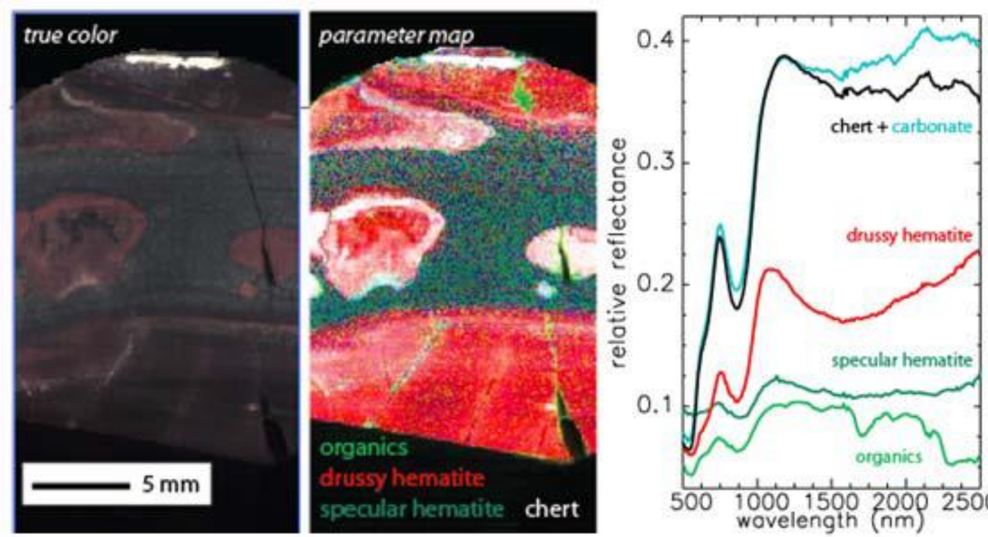
Vegetation health and productivity

Imaging spectrometers in the solar system:
VIMS (Saturn), Omega, CRISM (Mars), M3, HySI (Moon), VIRTIS
Imaging spectrometers orbiting Earth:
Hyperion, MERIS, Artemis, HICO plus several airborne systems

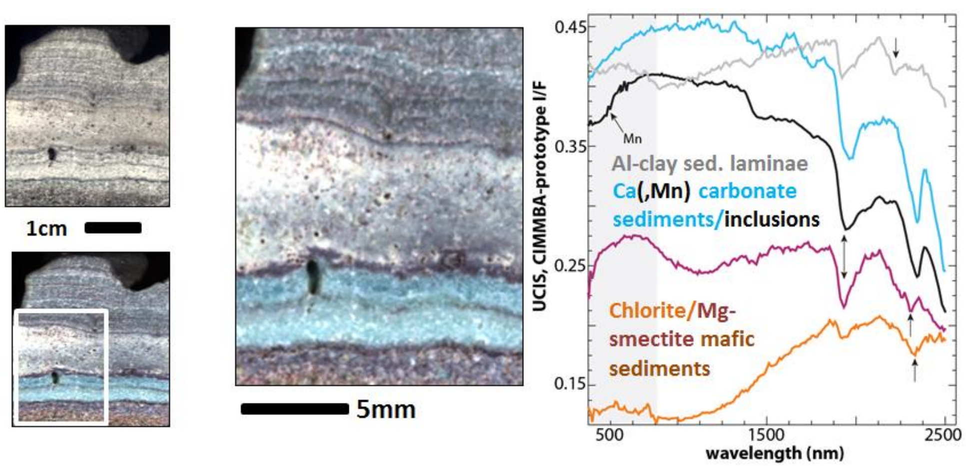
REFLECTANCE MICROSPECTROSCOPY



Bulk and microscopic spectra comparison



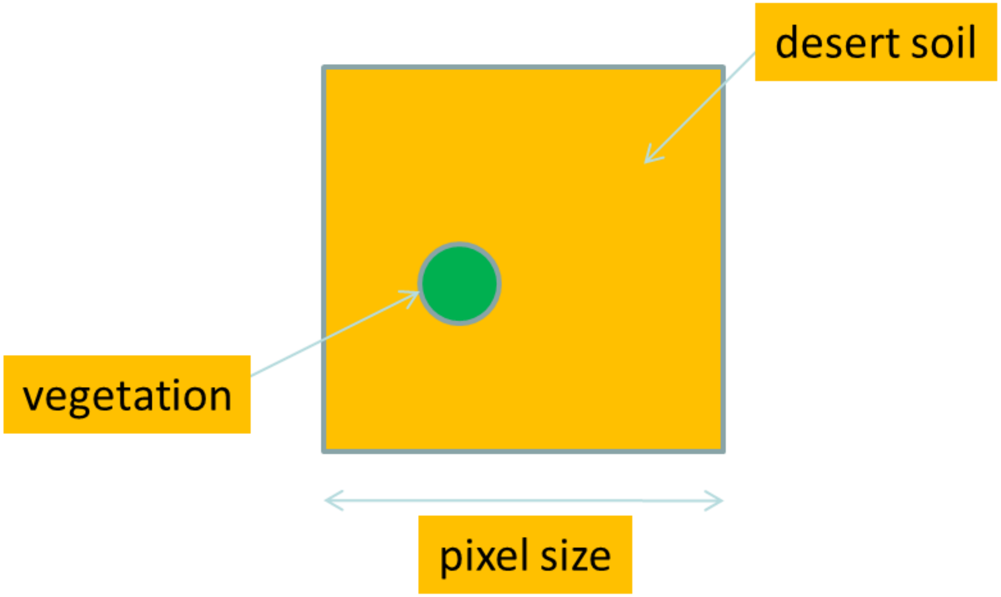
Banded iron formation: RGB/860,1750,2210 nm mapping of mineral phases. Single pixel or 3x3 spectra reveal Fe(III) oxides, chert & organics



Stromatolite in visible and SWIR pseudocolor. Single grain resolution within the sandstone & single pixel spectra from location show distinctive sources of sediments and two generations of carbonate. Above the carbonate are aluminum-rich clay minerals and below it are clay minerals that include magnesium-rich chlorites and smectites.

Mouroulis, et al, Appl. Spectrosc. 62, 2008
Van Gorp et al, J. Appl. Rem. Sens. 8, 2014

<u>**Imaging spectroscopy**</u> vs. Hyperspectral imaging



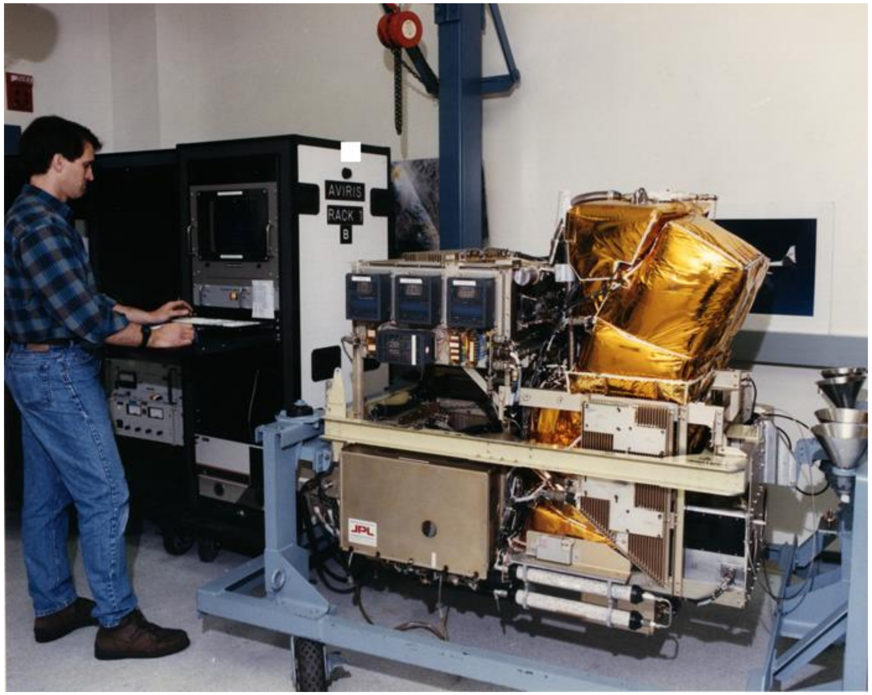
Vegetation is not resolved spatially (not imaged) but it can be resolved spectrally. Requirement for resolving spectral mixtures is very tight, ~1% or as small as possible.

Imaging spectroscopy: Identification through spectroscopy of spatially resolved or unresolved features, together with a map of their location.

“Hyperspectral imaging” implies a spatially resolved image with too many spectral bands.

Not mere semantics: Spatial resolution requirements are different if imaging is paramount (critical vs. > Nyquist)

Airborne Visible/Infrared Imaging Spectrometer

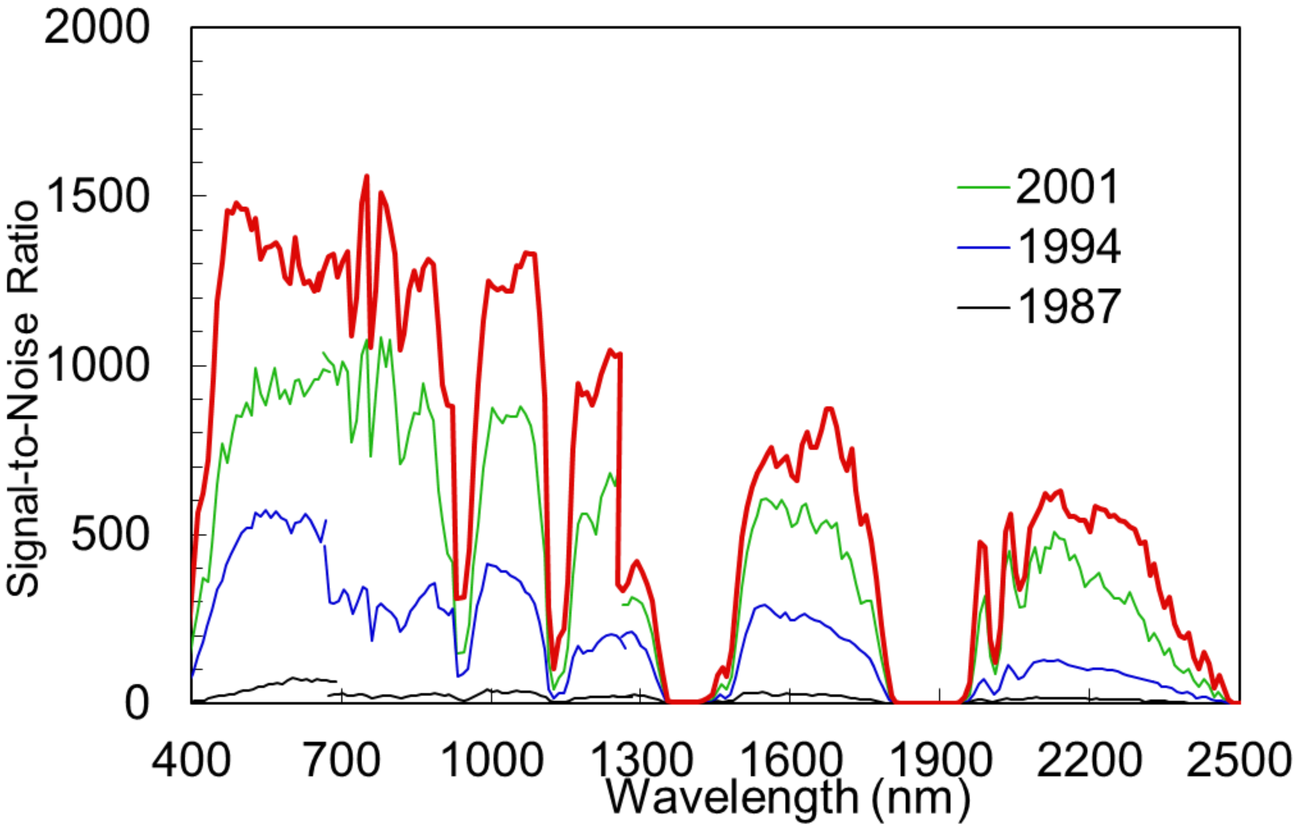


AVIRIS is designed with 200 μm detectors and F/1 optics. It is hard to imagine larger detectors or faster optics.

First flight 1987, has flown every year since 1989.

Vane et al, Rem. Sens. Environment 44, 1993
Green et al, Rem. Sens. Environment 65, 1998

AVIRIS SNR through the years



Continuous improvements and upgrades have kept AVIRIS at the forefront of airborne science.

Response Uniformity

- Any point on the ground yields calibrated, physically plausible spectral signature
- A spectral signature arises from a well-defined area on the ground

Maximum uniformity is achieved by a whiskbroom sensor with a single fiber connecting telescope and spectrometer.

AVIRIS is close to ideal (four distinct fibers connected to four spectrometers)

COMPACT INSTRUMENTS ENABLED BY PUSHBROOM ARCHITECTURE

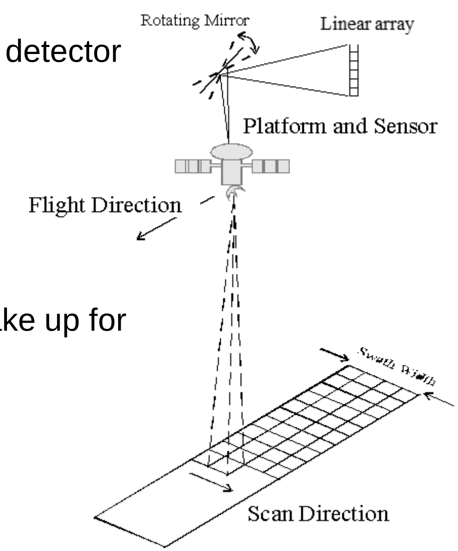
WHISKBROOM

Inherently uniform
(all spectra acquired by same detector array)

Easier to calibrate
(linear detector array)

Inherently large
(requires large aperture to make up for short integration time)

Requires scan mirror



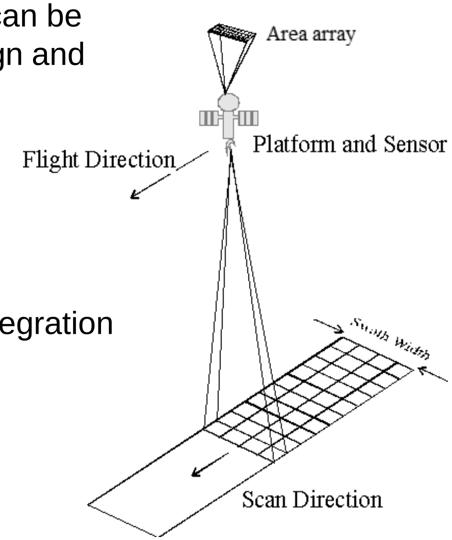
PUSHBROOM

Inherently non-uniform – but can be made uniform by careful design and implementation

Harder to calibrate
(area detector array)

Inherently small
(takes advantage of longer integration time)

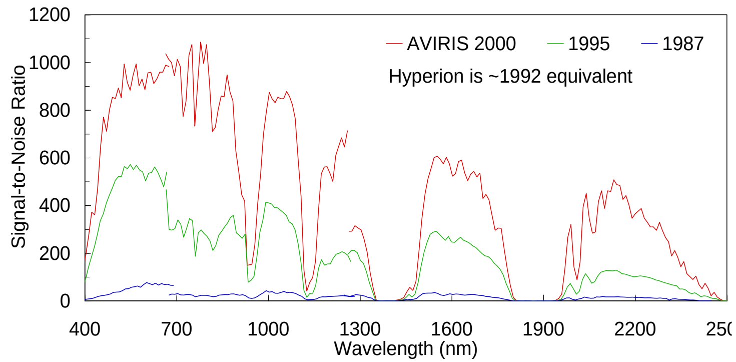
No moving parts



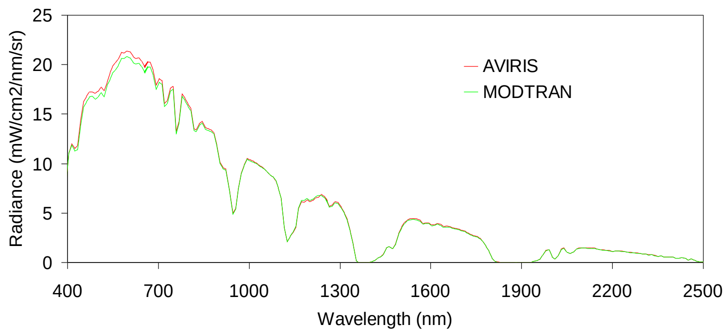
By integrating hundreds/thousands of simultaneous spectrometers on a single FPA, the pushbroom architecture achieves great size reduction, but requires also significant technology development and effort to achieve the same spectral purity, that is, eliminate spatial/spectral crosstalk.

What is needed in the instrument/measurement:

• High Signal-to-noise ratio
required for molecular spectroscopy

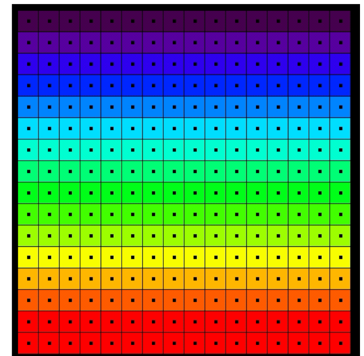


• Excellent calibration for quantitative results (spectral, radiometric, spatial)

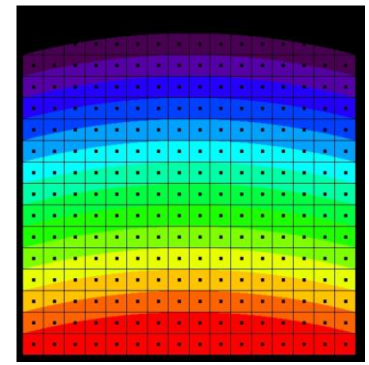


Green, Appl. Opt. 37, 1998
Mouroulis & McKerns, Opt. Eng. 39, 2000

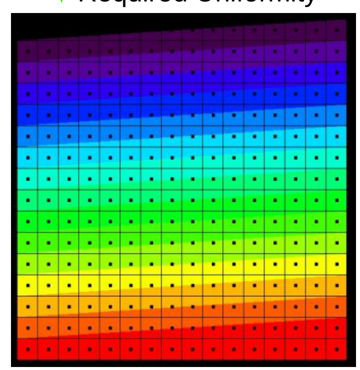
• Uniformity is required for
spectroscopy in the image domain



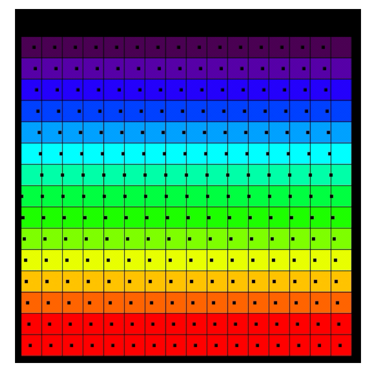
√ Required Uniformity



X Failure by “frown”



X Failure by twist

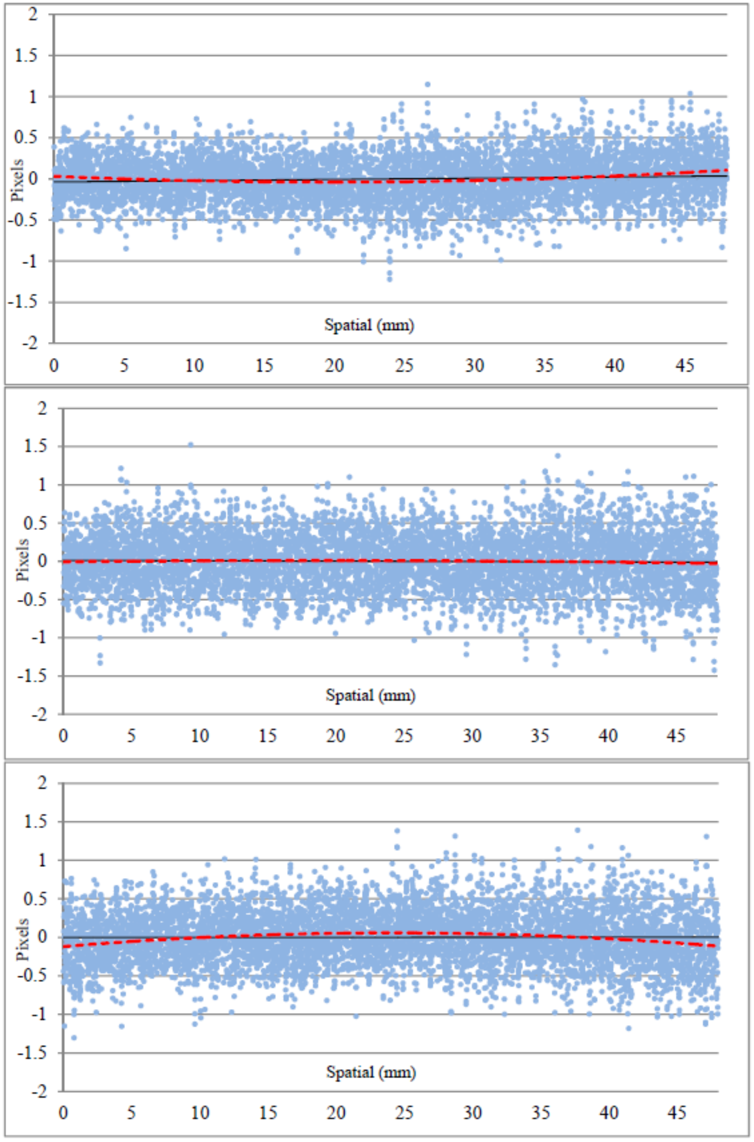


X Failure by
Spectral-IFOV-shift

4-1

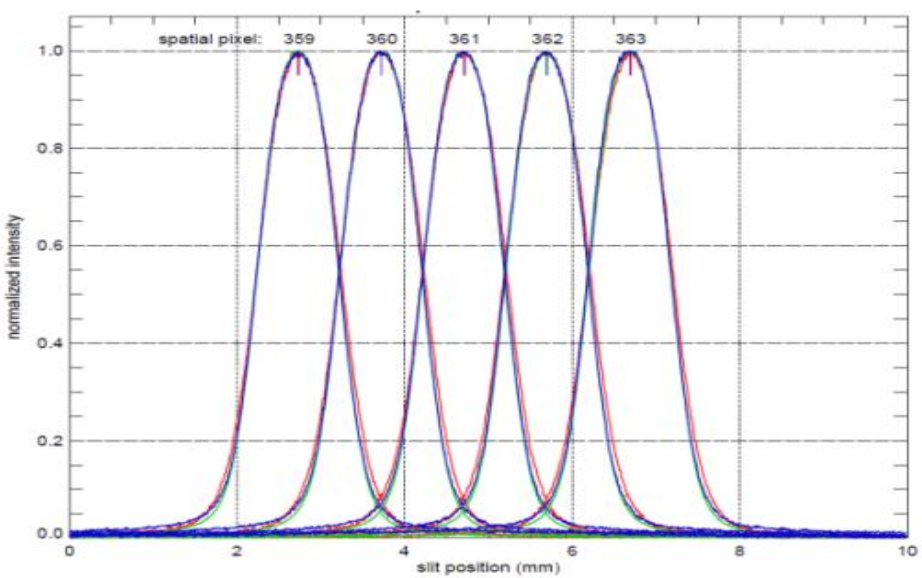
Geometric aspects of uniformity

How well can geometric aspects of uniformity be corrected?



- Demonstrated to date < 1% smile (<300 nm) over 48 mm slit
- < 2% keystone (<600 nm) over 400-2500 nm band

with proper tolerancing, alignment, and measurement techniques



Bender et al, Proc. SPIE 9222 (2014)
Bender et al, Proc. SPIE 8158 (2011)

Non-geometric aspects of uniformity

- Spectral uniformity against spatial field: all “spectrometers” have the same calibration in terms of spectral response shape and width

- Spatial uniformity against wavelength: all colors arise from same patch on the ground

Even if detailed calibration is attempted, data extraction and correction algorithms become extremely complicated by having to account for different calibration for every pixel.

Variation of the response function shape and width causes similar effects as the variation in centroid location.

Full characterization accounts for any variation of light spilling outside the pixel.

If response functions are well approximated by Gaussians or similar forms, variation can be characterized in terms of first and second moments, or centroid and FWHM.

Green, App. Opt. 37, 1998
Mouroulis, Green & Chrien, Appl. Opt. 39, 2000
Skauli, Opt. Express 20, 2012

Response function computation and assessment

Slit decouples telescope from spectrometer in one direction:

This means (to a first approximation):

•Along-track spatial response function (ARF) depends on front optic only

•Cross-track spatial response function (CRF) depends on the complete system (coherent coupling of front optics and spectrometer aberrations)

•Spectral response function (SRF) depends on the spectrometer only

First approximation means incoherent approximation that ignores slit diffraction.

Slit causes incident light to be diffracted outside the spectrometer aperture. This is ignored in raytrace models and in all raytrace-based wavefront models.

Partially coherent computation accounts for slit diffraction but is labor and resource intensive.

Incoherent approximation is generally good to <~15% in absolute terms, and significantly better in relative terms (e.g. determining difference between similar systems, different field points in the same system, etc.)

Mielenz, J. Opt. Soc. Am. 57, 1967
Mouroulis & Green, Proc. SPIE 6667, 2007

Response Function Computation

$$ARF = rect(y_0) \otimes LSF_T(y) \otimes rect(y_t)$$

$$CRF = LSF_{sys}(x) \otimes DET(x)$$

$$SRF = rect(y_0) \otimes LSF_{sp}(y) \otimes DET(y)$$

Incoherent approximation equivalent:

•In ARF computation, the spectrometer is ignored. Equivalent to placing a large detector immediately behind the slit (collects all light).

•In CRF computation, front optics and spectrometer aberrations are added as phase terms without considering the wavefront clipping by the slit.

•In SRF computation, the front optic is ignored. Equivalent to illuminating the slit with an integrating sphere (no aperture present before the slit).

Telescope design principles

1. Zero transverse chromatic aberration (or <1% of a pixel)
2. Minimum (ideally zero) variation of response with wavelength – over 2.5 octaves
3. Maximum transmission over broad band
4. Close pupil matching with spectrometer not required (but oversize apertures)

These imply:
1. Typically reflective telescope
2. Diffraction spread contained within the pixel/slit width (low F-number)
3. Minimum number of optical elements
4. Designs with virtual aperture stop permitted

Telescope designs available
- Three-mirror anastigmat (more mirrors possible, but accept transmission loss)
- Two-mirror modified Schwarzschild
- Cassegrain with field corrector if required (refractive or reflective corrector possible)

Purely refractive designs severely limited (some examples in Mouroulis Proc. SPIE 6667 (2007) and Fisher & Welch, Proc. SPIE 6062 (2006))

Telescope design examples

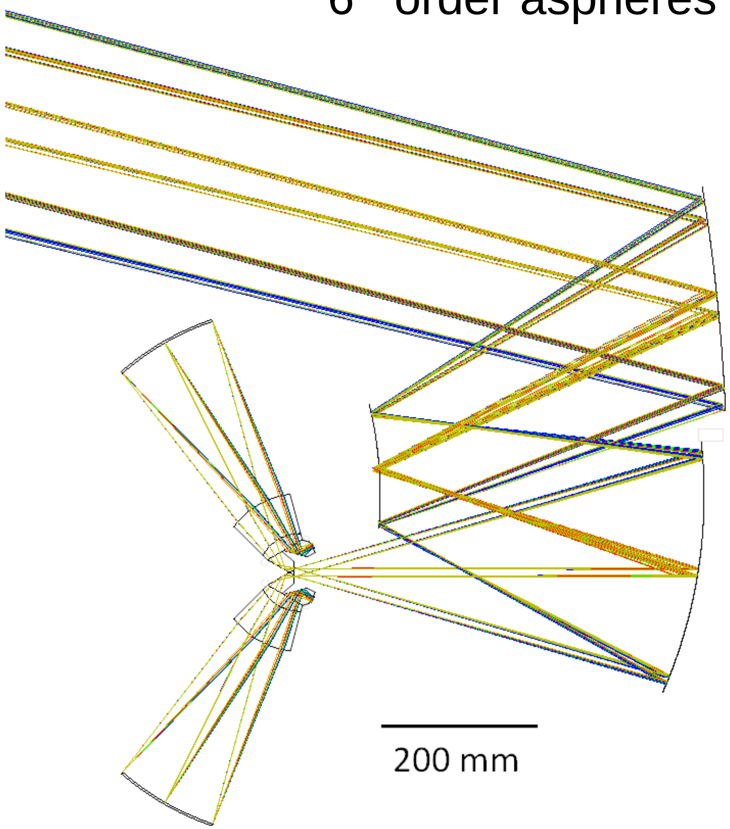
TMA combines relatively compact size with the ability for wide field and relatively low F-number
Preferred design for medium focal length and field. Unobscured.

Two-mirror telescope combines very low f-number with wide field but is large relative to focal length
Preferred choice for medium to short focal length, wide field, low f-number. Unobscured.

Cassegrain is needed for long focal length designs due to compact size.
Refractive or reflective corrective relays can widen field. Obscured.

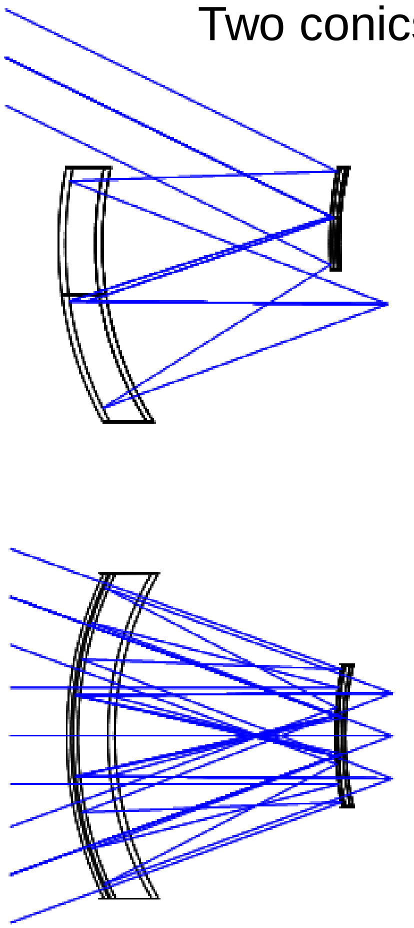
TMA example, 420 mm, F/1.8, 16 deg FOV, 18 um pixel size, 6400 cross-track pixels

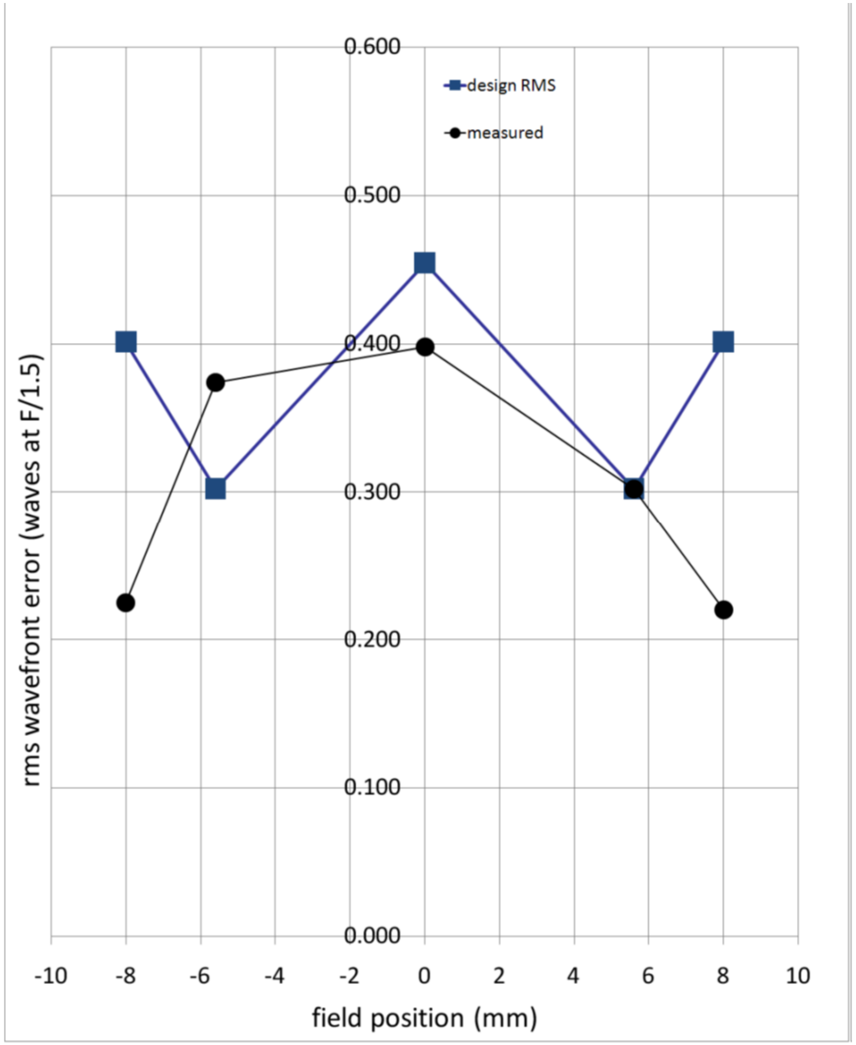
6^{th} order aspheres



x-field	ensquared energy fraction	ensquared energy/diff. limit
1	0.87	0.96
-4	0.88	0.97
-6	0.86	0.95
-7	0.83	0.92
1	0.84	0..93
6	0.87	0.96
8	0.87	0.96
9	0.84	0.93

TMA example, 30 mm, F/1.4, 33 deg FOV, 30 um pixel size, 640 cross-track pixels





Mouroulis et al, Proc. SPIE 8032, 2011

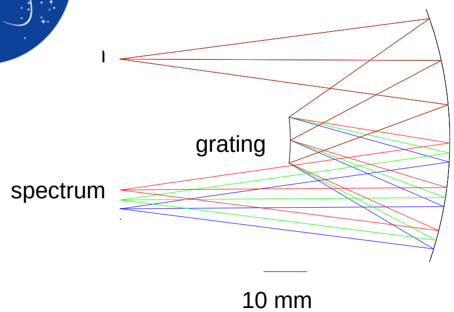
Cassegrain:

- Field can be extended to over 1degree with various types of correctors
- Achromatized refractive corrector with all SiO_2 or CaF_2 elements possible
- Reflective corrector with a 3-mirror relay is preferred due to both transmission and stray light control

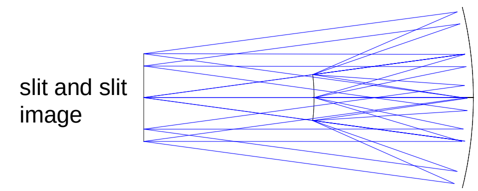
Spectrometer design principles

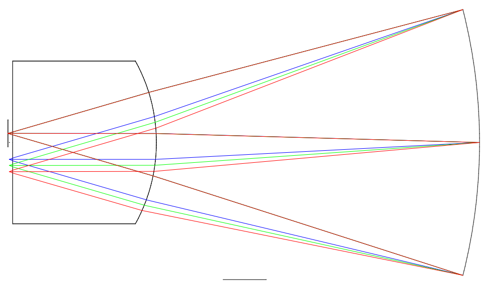
1. Geometric distortions controlled to 1% of a pixel at design (~3% after tolerancing)
2. Preferred stop location is at the grating or dispersive element
3. Accept degraded spot sizes to improve uniformity
4. Include uniformity operands in merit function
5. Maintain >75% of diffraction energy within pixel at all wavelengths and fields
6. Integrate (deterministic part of) stray light assessment into first design
7. Assess uniformity and image quality in terms of spatial and spectral response functions, and not wavefront, MTF, rms spot size, etc. etc., except as any of the faster-to-compute measures can be shown to correlate with response functions

Concentric spectrometer forms are ideally suited to pushbroom architectures

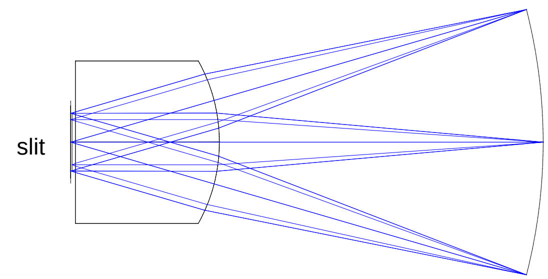


Offner



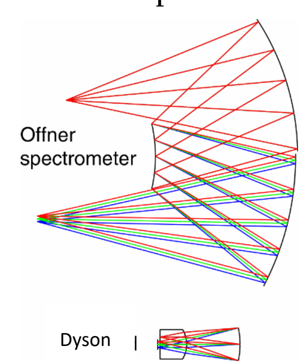


Dyson



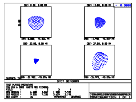
Offner	Dyson
All reflective (broad band, athermalization)	High throughput
Can reach high spectral resolution	Miniature size
Weaker detector ghosts	Easiest alignment

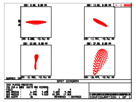
Size comparison between Offner and Dyson with the same specifications (@F/1.6)



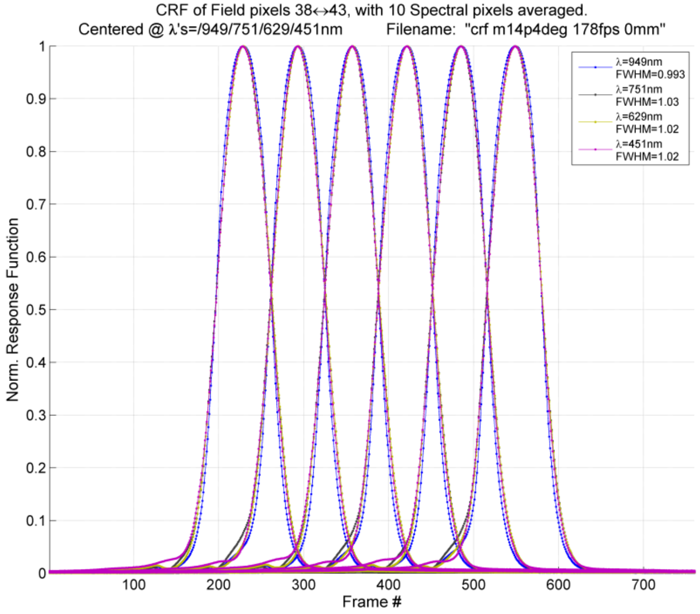
Dyson, J. Opt. Soc. Am.(1959), Offner, Opt. Eng. (1975), Mertz, Appl. Opt. (1977), Kwo et al, Proc. SPIE 818 (1987), Maker et al, Proc. SPIE CR62 (1996), Mouroulis, Proc. SPIE 7298 (2009)

These design and assembly/alignment techniques lead to high uniformity

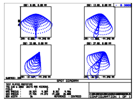


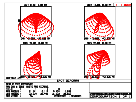


High uniformity through wavelength of cross-track spatial response example



Aberration may be intentionally increased to improve uniformity



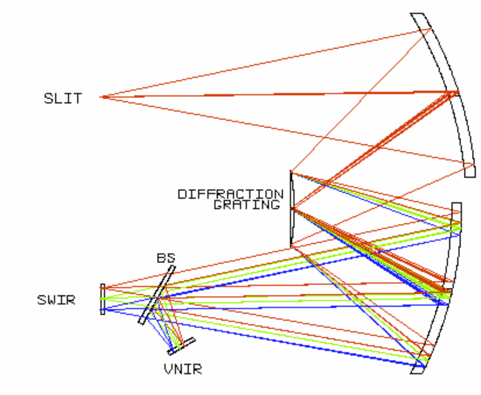


Mouroulis, Green & Chrien, Appl. Opt. 39, 2000

Spectrometer design examples

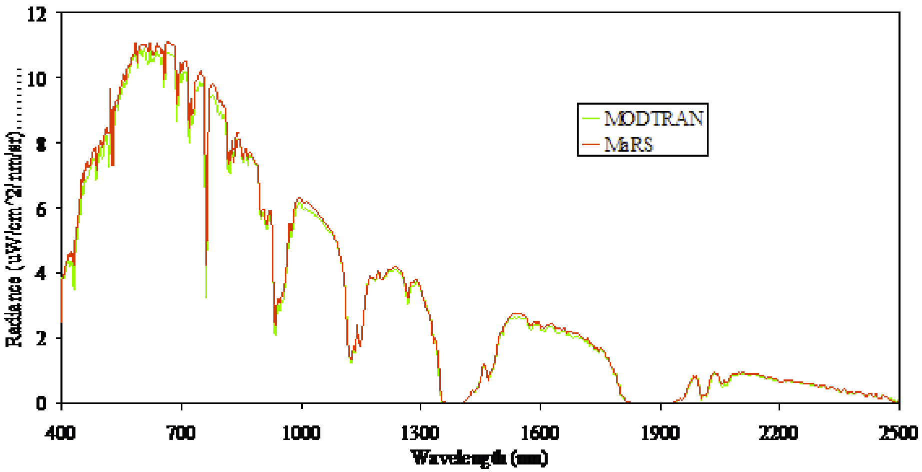
Offner imaging spectrometer system development at JPL

- 2006: MaRS (airborne)
- 2008: M3 (Moon orbit)
- 2011: Next Generation Imaging Spectrometer (airborne)
  CAO, NEON, AVIRISng
- 2012: MSS (airborne)
- 2012: Ultra-compact Imaging Spectrometer (in-situ or orbit)



MaRS 2-FPA design

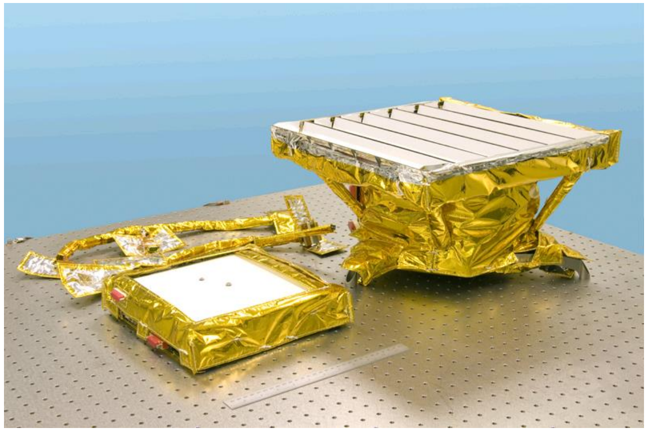
Installation



Radiometric calibration >97%

Simi et al, Proc. SPIE 7457, 2009

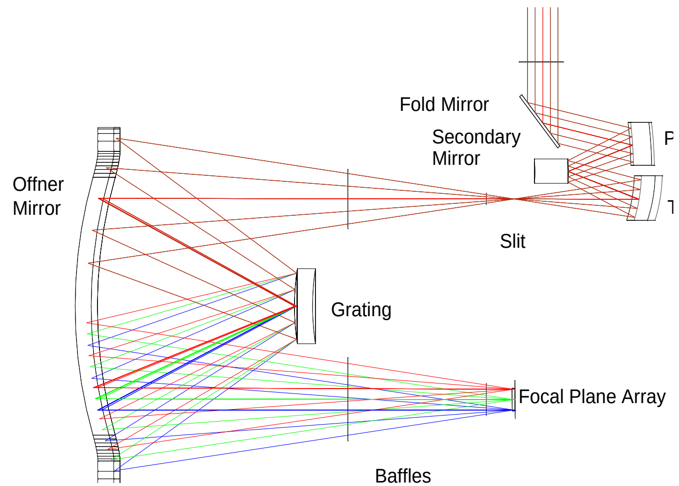
The Moon Mineralogy Mapper (M3) on Chandrayaan I



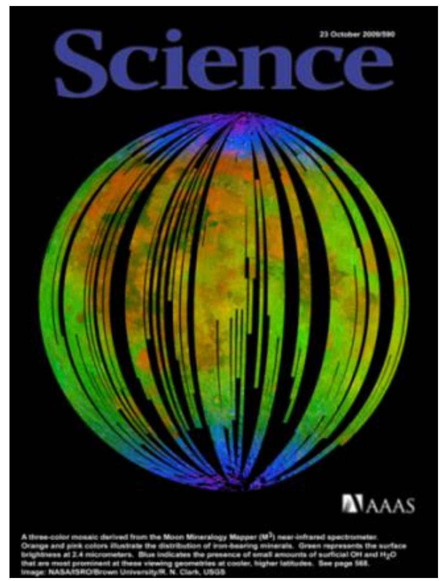
Launched 22 Oct. 2008

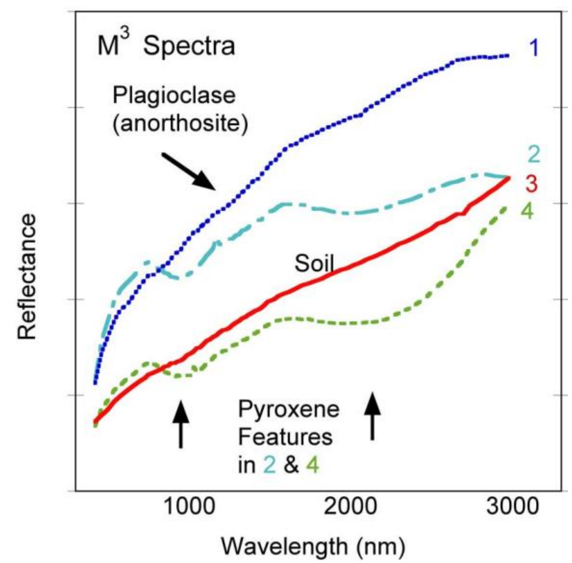
8 kg mass, 24 month build

- 430-3000 nm band
- 10 nm sampling
- 600 cross track pixels



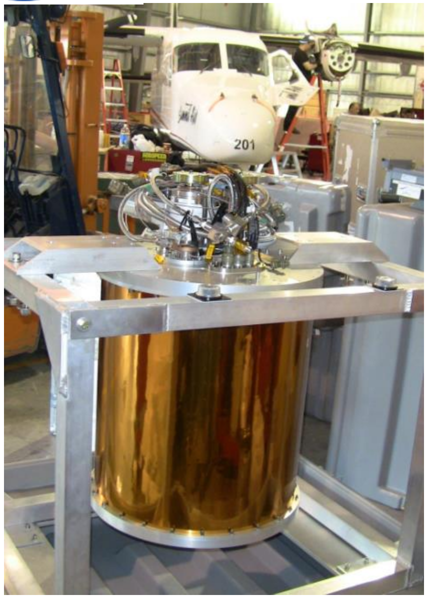
1-FPA, 4-mirror telescope



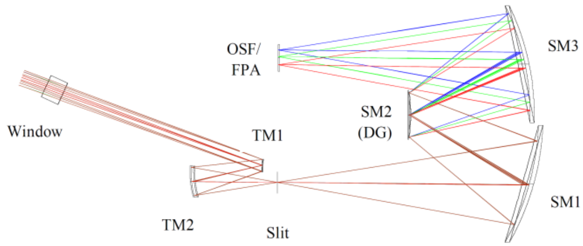


Pieters et al, Science 326, 2009
Green et al, J. Geophys. Res. Planets 116, 2011
Mouroulis et al, Opt. Engineering 46, 2007

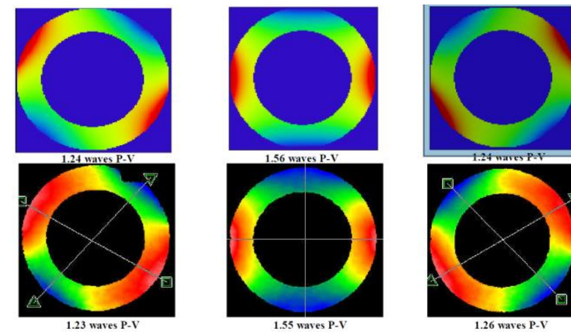
Next Generation Airborne Imaging Spectrometer



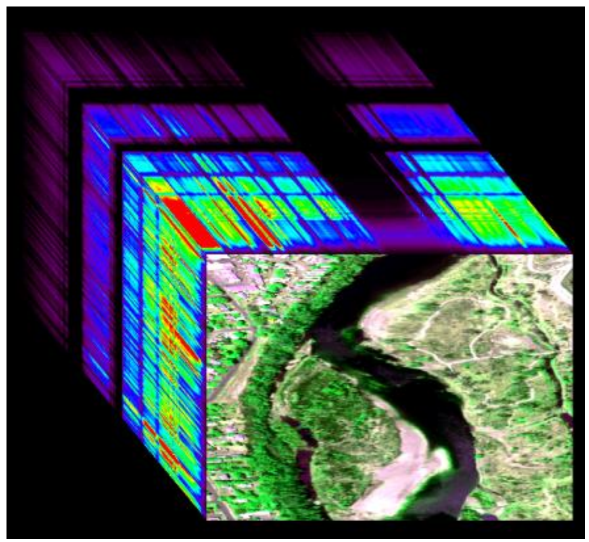
NGIS deployment



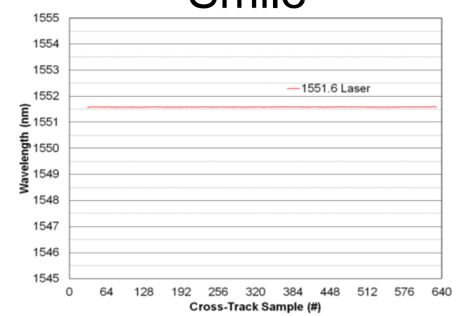
1-FPA, two-mirror telescope



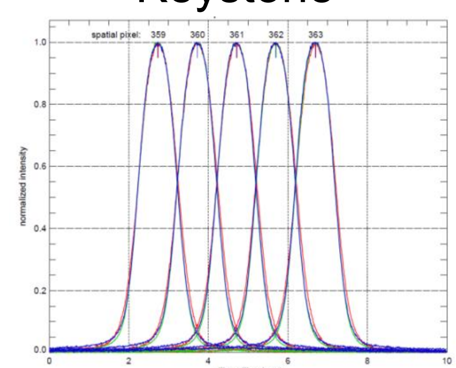
Alignment techniques to achieve high uniformity

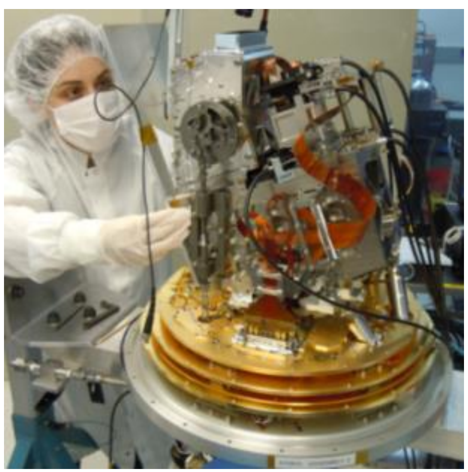


“Smile”



“Keystone”

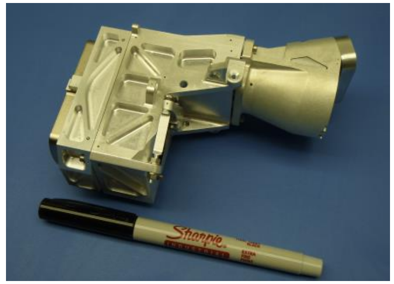




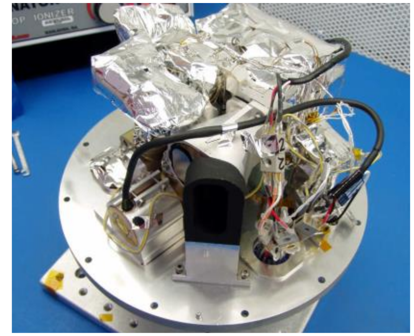
Bender et al, Proc. SPIE 7812, 2010
Bender et al, Proc. SPIE 8158, 2011

Offner imaging spectrometer system development at JPL
Ultra-compact Imaging Spectrometer (UCIS) for in-situ mineralogy

Miniaturized full-range (500-2600 nm) spectrometer system

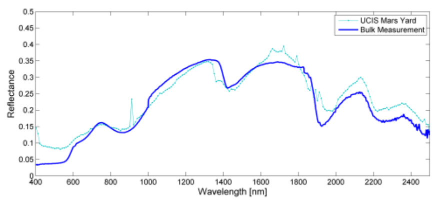


Optical bench



Full system in vacuum enclosure

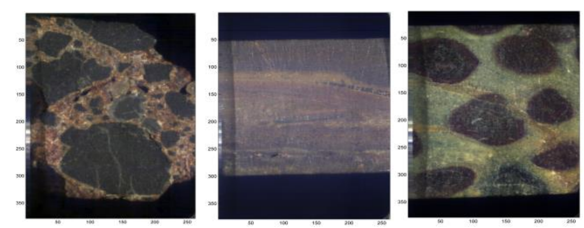
On tripod for scanning

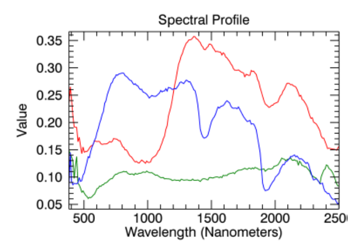


Critical spectral bands identified

Wide angle scan with a spectrum recorded for every point

In the field





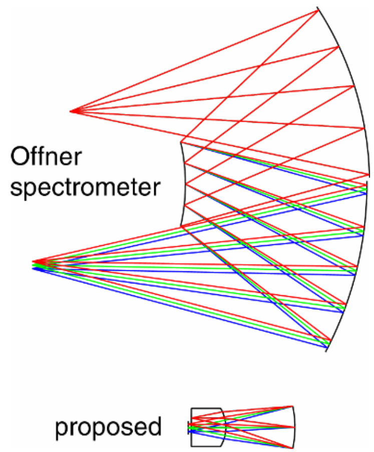
Microscopic mode: spatial resolution 80 μm

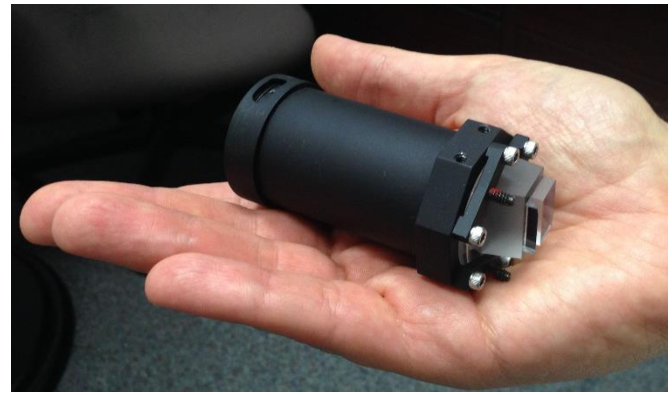
Van Gorp et al, Proc. SPIE 8158, 2011
Van Gorp et al, J. Appl. Rem. Sens. 8, 2014

Dyson imaging spectrometer development at JPL

Dyson design offers even more compact size, higher throughput, and low polarization sensitivity.

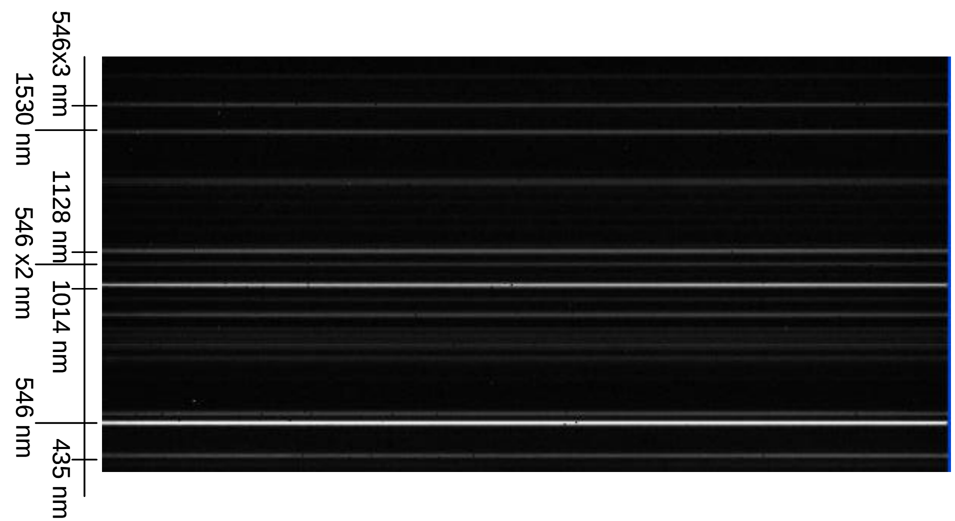
Size comparison between Offner and Dyson with the same specifications (@F/1.6)





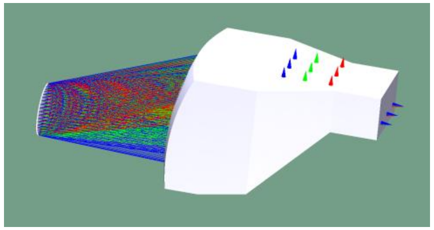
Complete assembly of Dyson spectrometer optics (400-1700 nm, F/1.8, 640 spatial elements)

Test spectra from Hg lamp



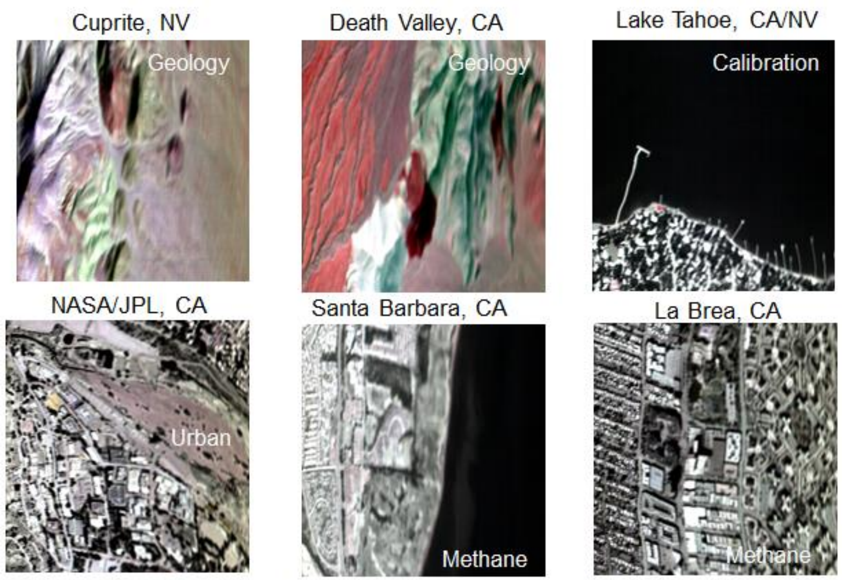
Mouroulis, SPIE Proc. 7298, 2009

HyTES: Hyperspectral Thermal Emission Spectrometer

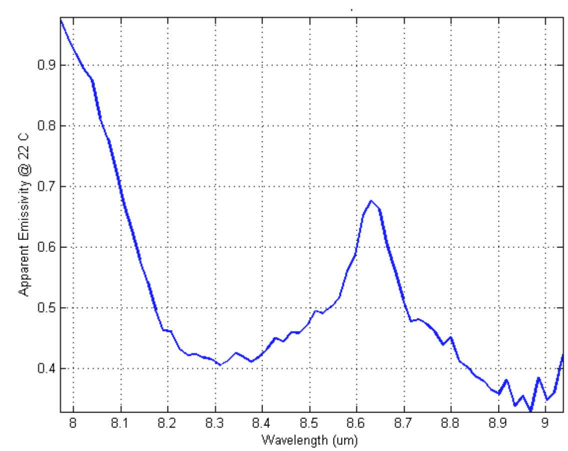


Miniature optical design

- 7.5-12 μm
- 50º FOV
- 512 spatial elements
- 256 spectral channels
- F/1.6 aperture



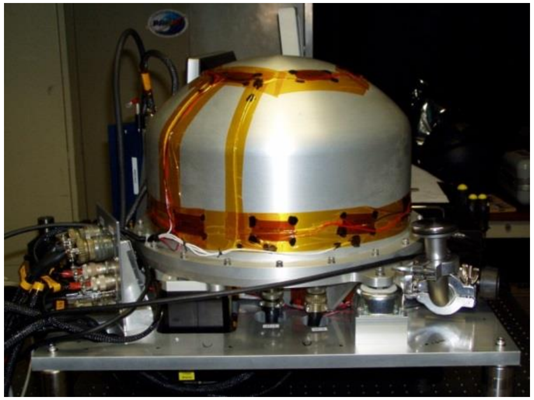
Bands 150 (10.08 μm), 100 (9.17 μm), 58 (8.41 μm), displayed at RGB each image is 495 x 512 pixels



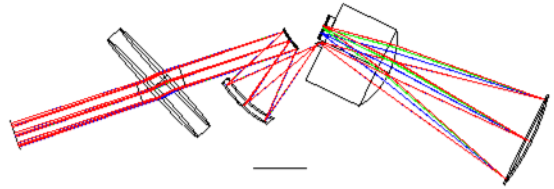
Measured emission spectrum of quartz

Johnson et al, Proc. SPIE 7457, 2009
Hulley et al, Atmos. Meas. Tech., 9, 2016

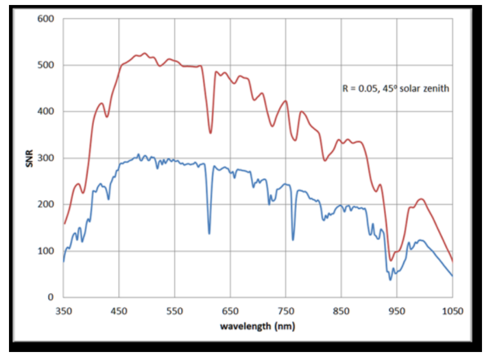
Portable Remote Imaging Spectrometer (PRISM) Coastal Ocean Sensor



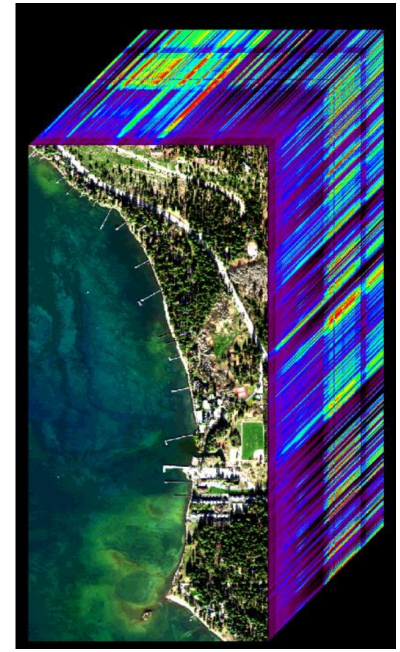
Sensor head installed in Twin Otter below



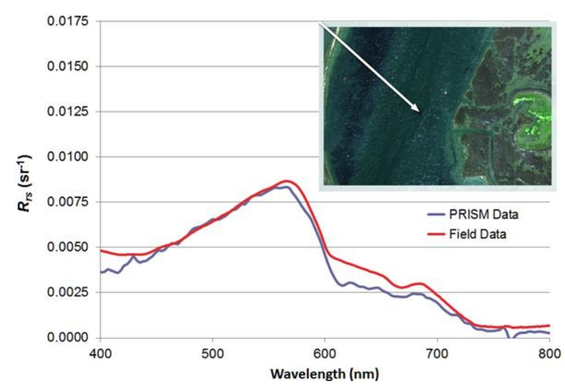
Fast and compact optical design that supports high uniformity and low polarization sensitivity



High Signal to Noise for dark targets



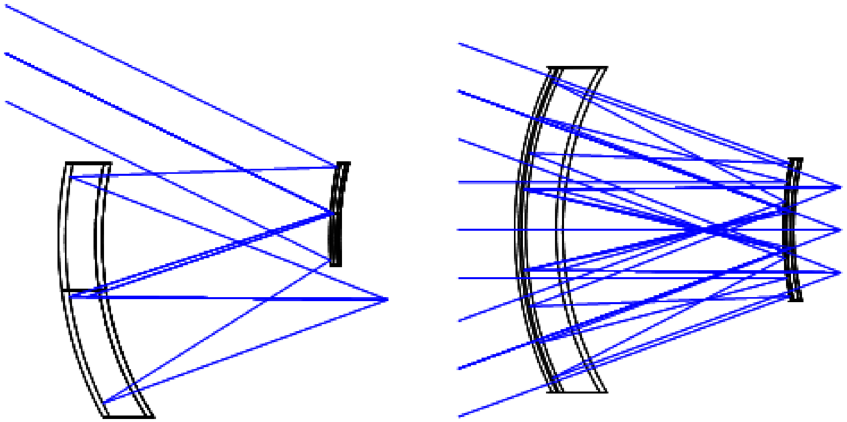
Spectral image cube from Lake Tahoe



Excellent agreement between PRISM and in-situ measured spectra

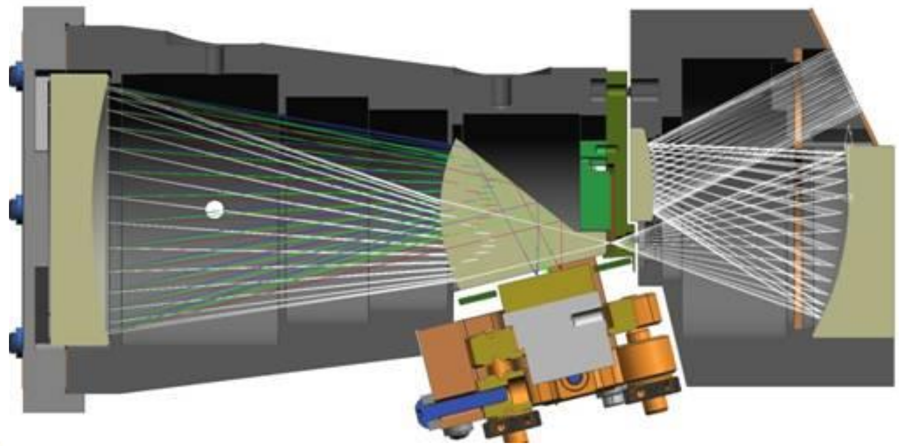
Mouroulis, Green & Wilson, Opt. Express 16, 2008
Mouroulis et al, Appl. Opt. 53, 2014

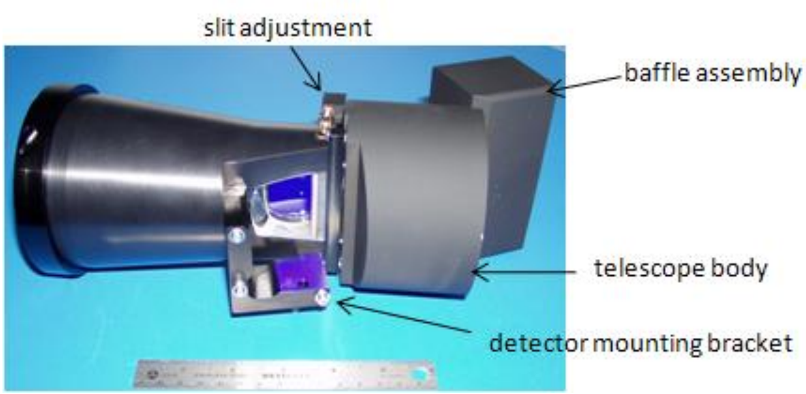
Maximum throughput, wide field spectrometer



Two-mirror design, F/1.4, 33^{o} FOV

- Two axially centered conics
- Tolerant to misalignment



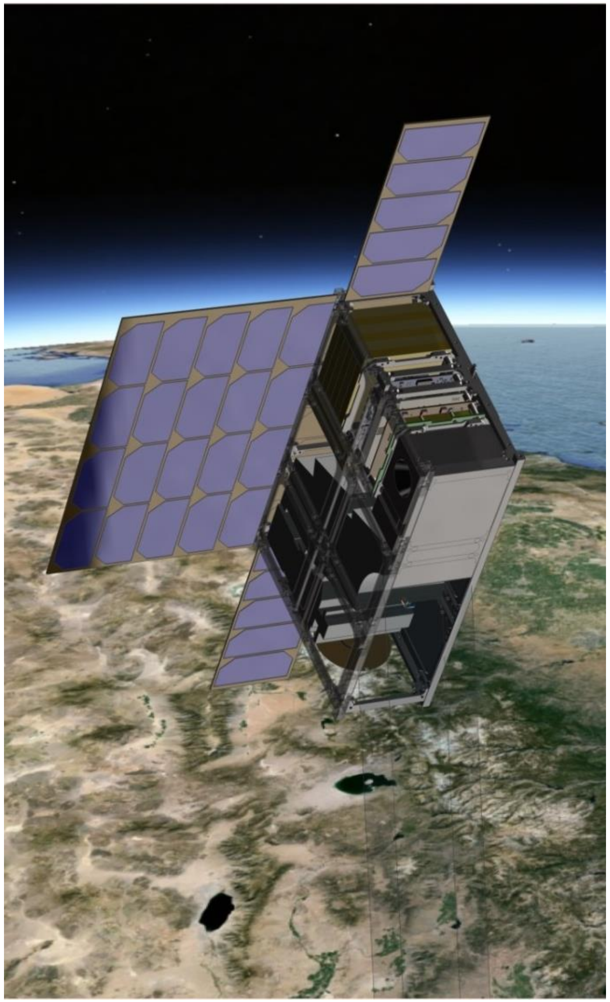


Mouroulis et al, Proc. SPIE 8032, 2011

Snow and Water Imaging Spectrometer (SWIS)

- A CubeSat–compatible imaging spectrometer (6U)
- High SNR
- High dynamic range
- On-board calibration
- More frequent/regular sampling relative to airborne instruments
- Intermediate to high resolution relative to global or flagship missions
- Relatively low-cost alternative

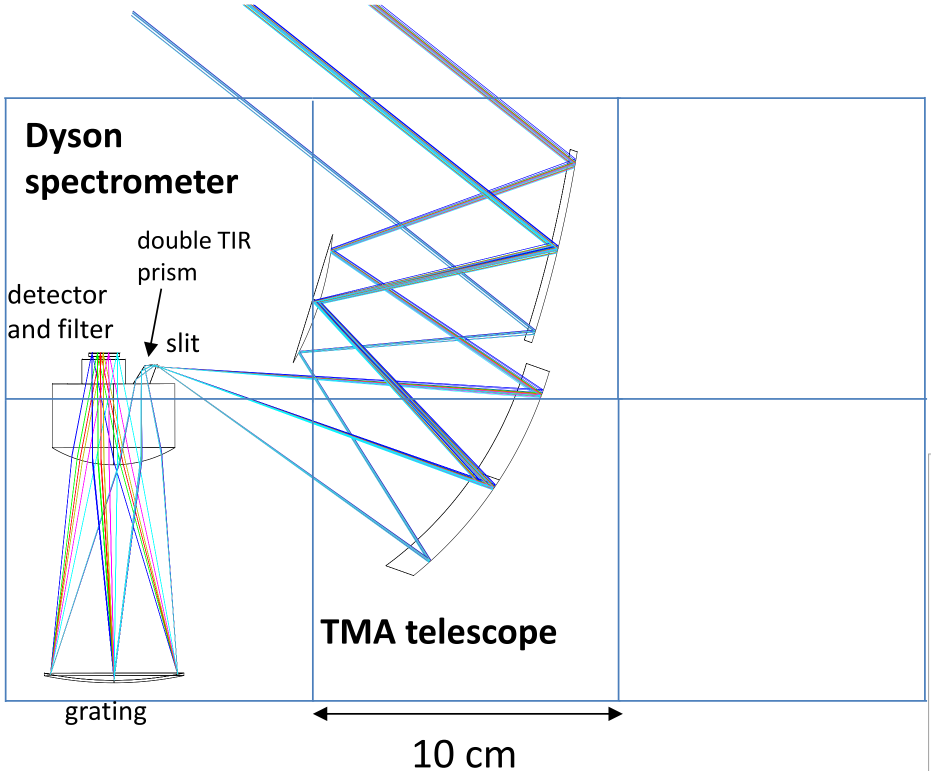
Addresses coastal waters and snow/ice cover applications



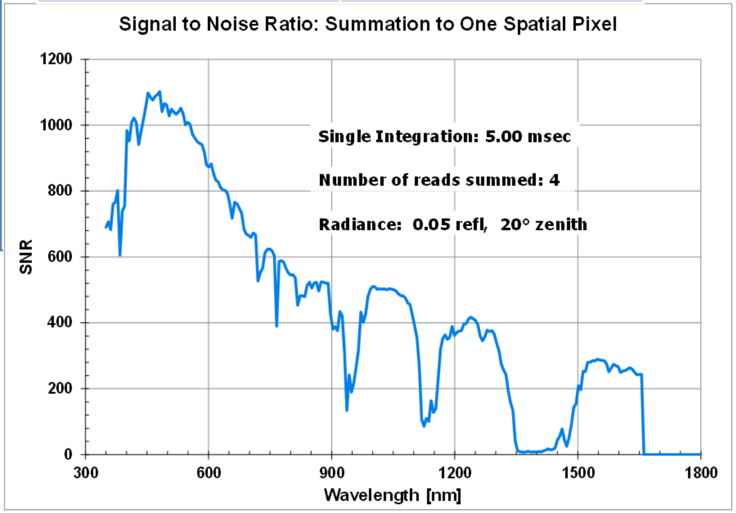
SWIS CubeSat, artist's concept

SWIS instrument specifications

Spectrometer and telescope inside 6U CubeSat frame



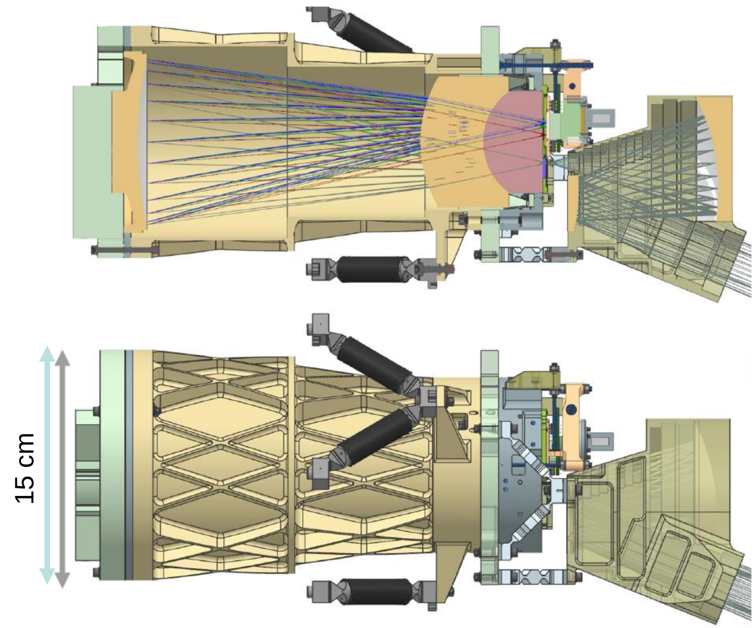
SWIS specifications	
Spectral range	350-1700 nm, single FPA
Spectral sampling	5.7 nm
Cross-track spatial elements	600 (+40 monitor)
Cross-track FOV	10°
Resolution	0.3 mrad
Detector pixel size	30 μm
Focal length	100 mm
F-no	1.8
Uniformity	95%



Mouroulis et al, Proc. SPIE 9222, (2014)

The Compact Wide and the Advanced Land Imaging Spectrometer (CWIS and ALIS)

- Landsat swath and resolution challenging even for multispectral instruments (~6300 pixels cross track)
- Thematic Mapper (whiskbroom) finally abandoned in Landsat 8
- OLI replaces Thematic Mapper, pushbroom plus discrete filters
- Imaging spectrometer solution offers simultaneity of spectral bands and enhanced science capabilities
- Increase in number of spectral bands by an order of magnitude
- Challenging design, must be high SNR



Van Gorp et al, Proc. SPIE 9222, 2014

CWIS: 1600 x 30 μm pixels
ALIS: 3200 x 18 μm pixels

The Compact Wide and the Advanced Land Imaging Spectrometer (CWIS and ALIS)

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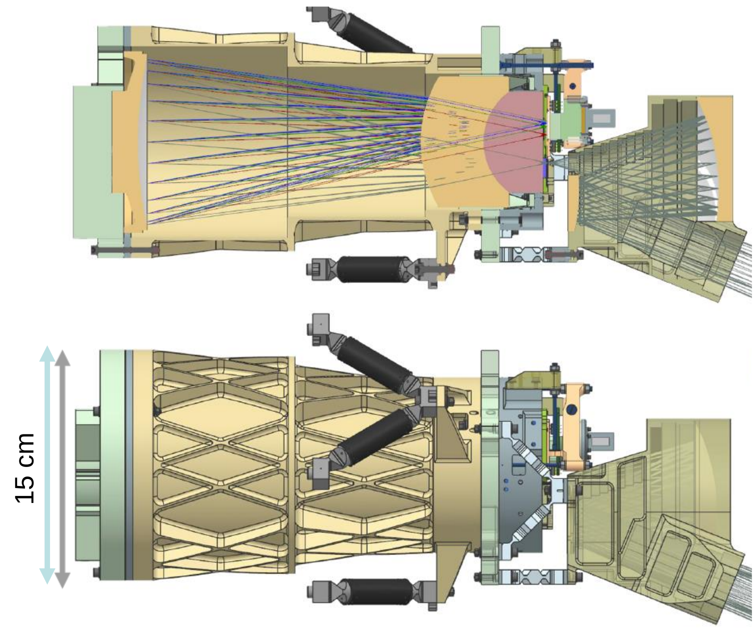


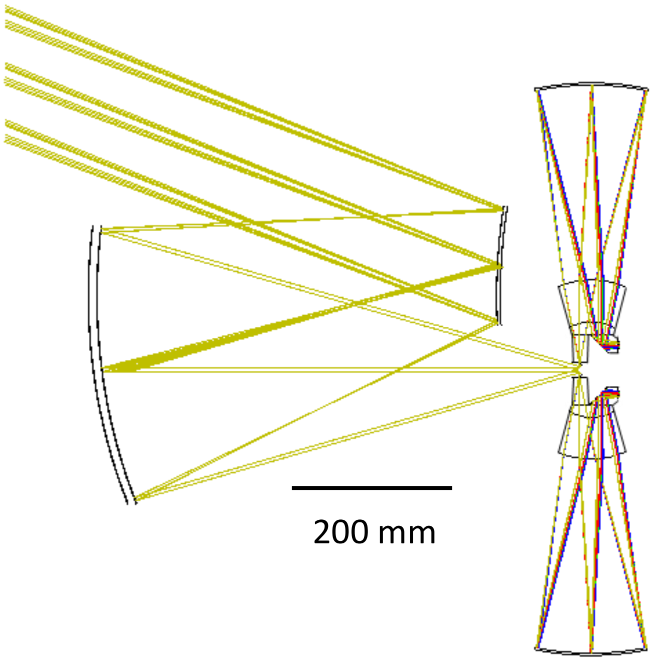
Van Gorp et al, Proc. SPIE 9222, 2014

CWIS: 1600 x 30 μm pixels
ALIS: 3200 x 18 μm pixels

ALIS SPECIFICATIONS

Parameter	Value
Scan type	Pushbroom
Cross-track spatial elements	6400 (2 x 3200)
Telescope focal length	420 mm
F-number	1.8
Telescope FOV	16^{o} x 1.3^{o}
Spectrometer magnification	-1
Detector pixel size	18 μm square
Slit length (one spectrometer)	57.6 mm
Spectral range	380 – 2510 nm
Spectral sampling	6.8 nm per 18 μm pixel
SNR	See Fig. 5
Spectral uniformity	90%
Spectral IFOV uniformity	90%

ALIS Design and optical performance



Two-mirror telescope allows simple folding.
TMA telescope also designed.

Enclosed energy in 18 μm width

Wavelength	x-direction (spatial)	Fraction of diffraction-limited
380	0.94	0.95
630	0.89	0.90
1200	0.85	0.88
2500	0.88	0.94

Wavelength	y-direction (spectral)	Fraction of diffraction-limited
380	0.96	0.97
630	0.93	0.94
1200	0.92	0.94
2500	0.89	0.95

spectrometer

Mouroulis et al, Opt. Eng. 55, 2016

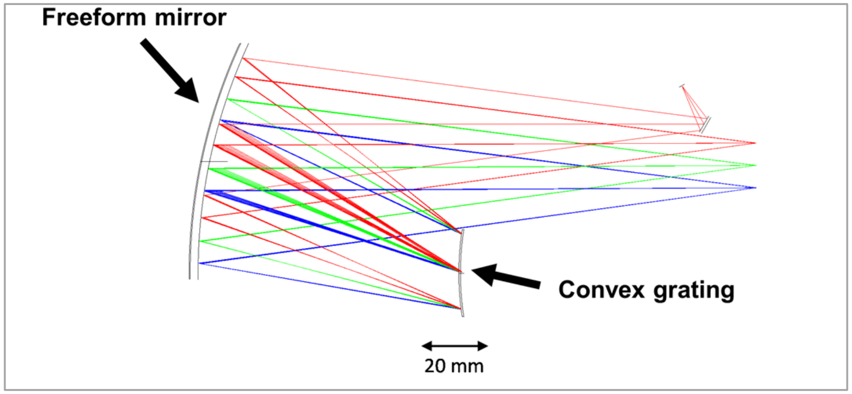
ALIS Response Function Assessment

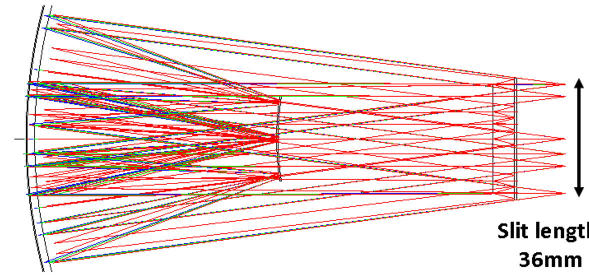
Distance from center of slit (mm)	SRF FWHM @380 nm (pixel fraction)	SRF FWHM @800 nm (pixel fraction)	SRF FWHM @1600 nm (pixel fraction)	SRF FWHM @2500 nm (pixel fraction)
0	1.31	1.33	1.35	1.42
11.25	1.32	1.35	1.36	1.4
18	1.33	1.38	1.37	1.39
22.5	1.33	1.39	1.38	1.39
28.8	1.33	1.39	1.37	1.44

wavelength	CRF FWHM at 1º	CRF FWHM at -4º	CRF FWHM at -6º	CRF FWHM at -7º
380 nm	1.12	1.1	1.13	1.26
800 nm	1.14	1.13	1.12	1.18
1600 nm	1.12	1.11	1.13	1.22
wavelength	**ARF FWHM at 1º**	**ARF FWHM at -4º**	**ARF FWHM at -6º**	**ARF FWHM at -7º**
380 nm	1.17	1.15	1.25	1.24
800 nm	1.2	1.17	1.27	1.23
1600 nm	1.19	1.16	1.21	1.22
2500 nm	1.25	1.18	1.18	1.33

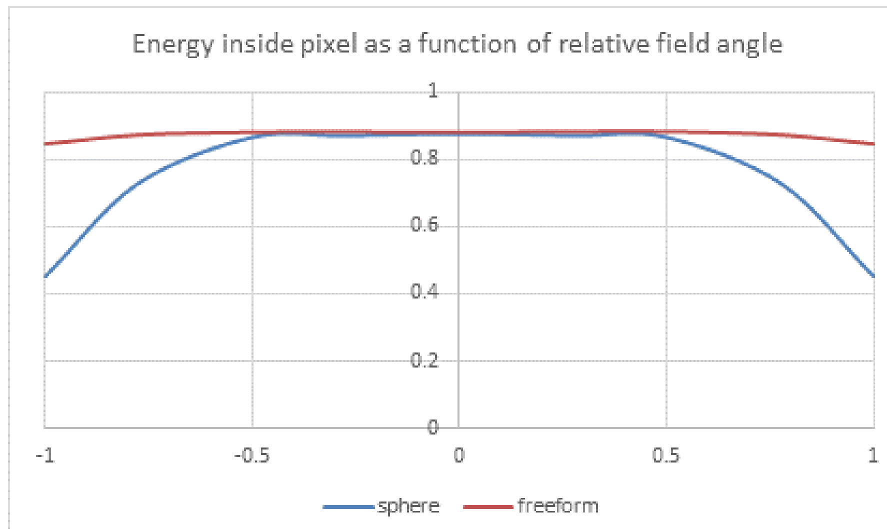
Freeform optics examples

High resolution, wide field Littrow-Offner for methane detection





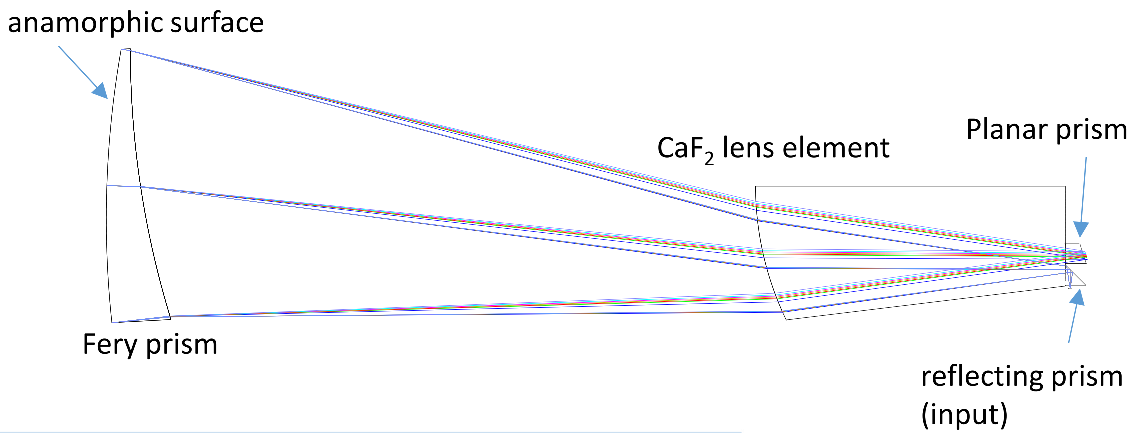
Parameter	Value
Spectral range (nm)	2,000-2,400
Spectral sampling (nm)	0.83
Detector pixel (µm)	30x30
Number of spatial pixels	1,240
F-number	4
Spot energy in pixel	>83% (>95% of diffraction limit)
Uniformity	>90%
Grating pitch (µm)	2.58
Size (optics)	90x90x190 mm



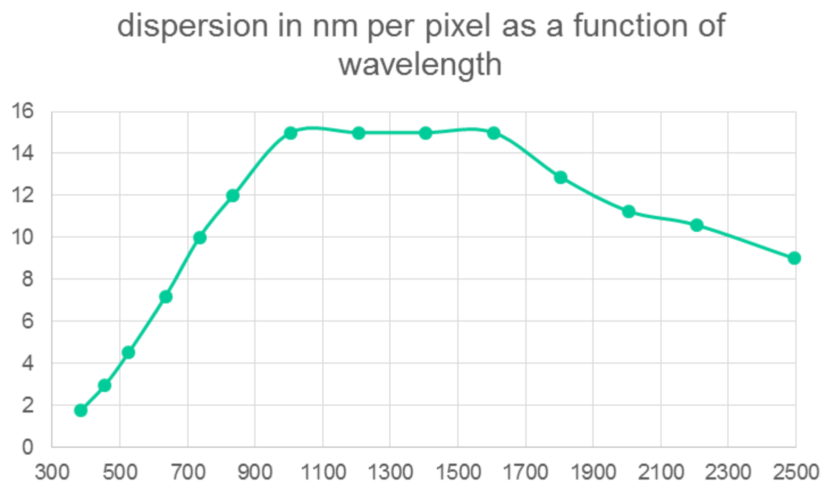
x-y polynomial surface with up to 14th order terms

Freeform surface doubles the field for the same spectrometer size

Broadband refractive Dyson-type spectrometer with conventional surfaces



Broad-band Prism Dyson Spectrometer (BPDS)	
Spectral range	380 – 2500 nm single FPA
Spectral sampling	< 15 nm per pixel (variable)
Cross-track spatial elements	2160
Detector pixel size	18 μm
F-no	2.5
Uniformity	>90%
Dispersive element	Infrasil reflecting Fery prism with anamorphic surface
Optical design	Dyson with CaF_2 lens element

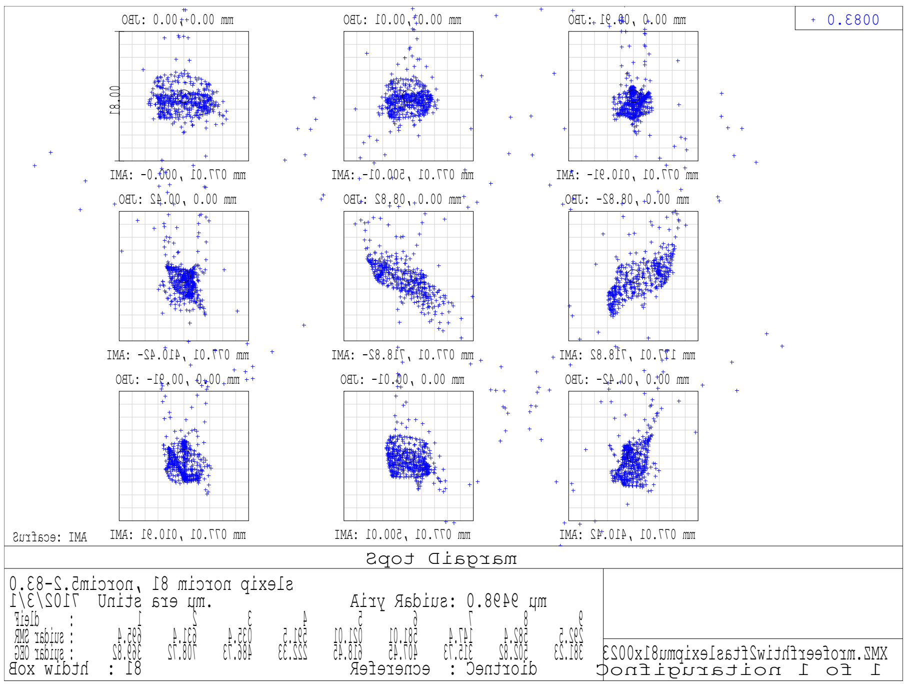


Broadband Prism Dyson Spectrometer with freeform surface

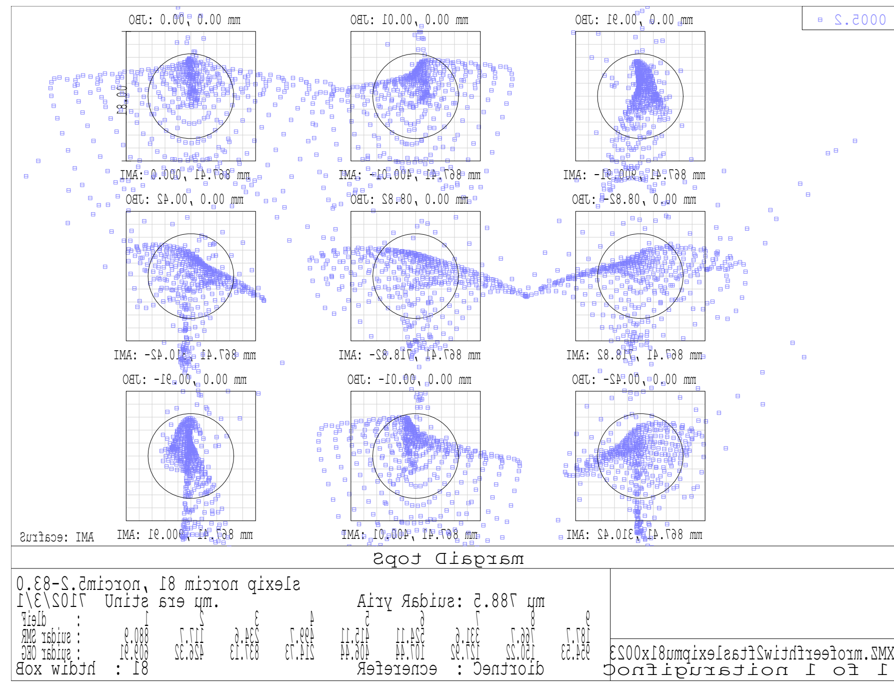
Broad-band Prism Dyson Spectrometer (BPDS)		BPDS with freeform surface	
Spectral range	380 – 2500 nm single FPA	Spectral range	380 – 2500 nm single FPA
Spectral sampling	< 15 nm per pixel (variable)	Spectral sampling	< 15 nm per pixel (variable)
Cross-track spatial elements	2160	Cross-track spatial elements	3200
Detector pixel size	18 μm	Detector pixel size	18 μm
F-no	2.5	F-no	2
Uniformity	>90%	Uniformity	>90%
Dispersive element	Infrasil reflecting Fery prism with anamorphic surface	Dispersive element	Infrasil reflecting Fery prism with anamorphic surface
Optical design	Dyson with CaF_2 lens element, spherical surface	Optical design	Dyson with CaF_2 lens element and freeform surface
Optics length	50 cm	Optics length	54 cm
Prism diameter	14 cm	Prism diameter	19.2 cm

For a modest increase in size, freeform surface allows simultaneous 1.5x increase in throughput and field while maintaining uniformity.

Spot sizes through field for 380 nm wavelength and 2500 nm wavelength, shown in 18 μm pixel box size. The optimization accounts for wavefront rather than spot size, so it actually maximizes energy inside the pixel. See next chart.

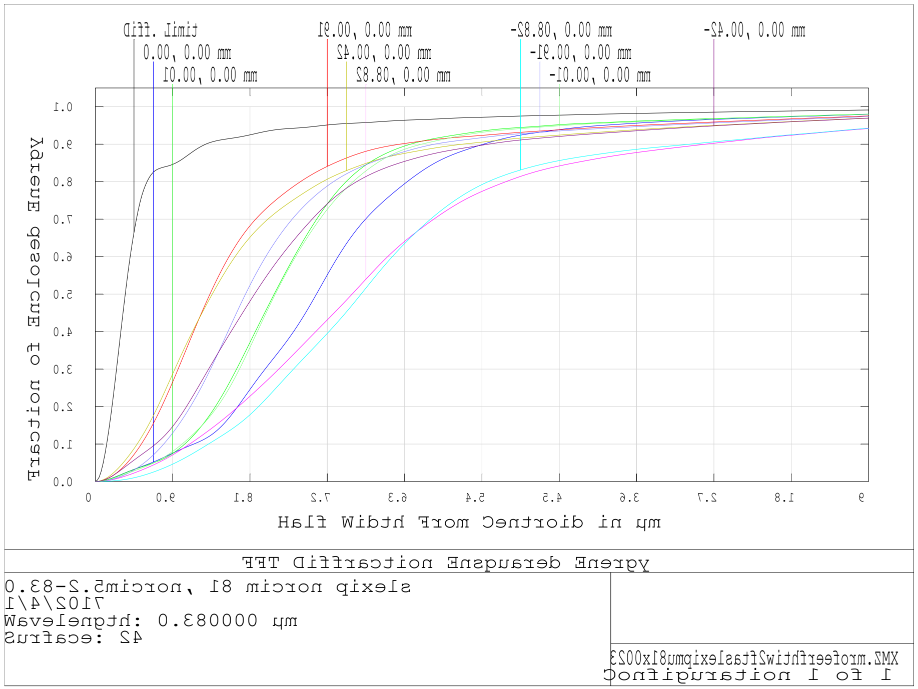


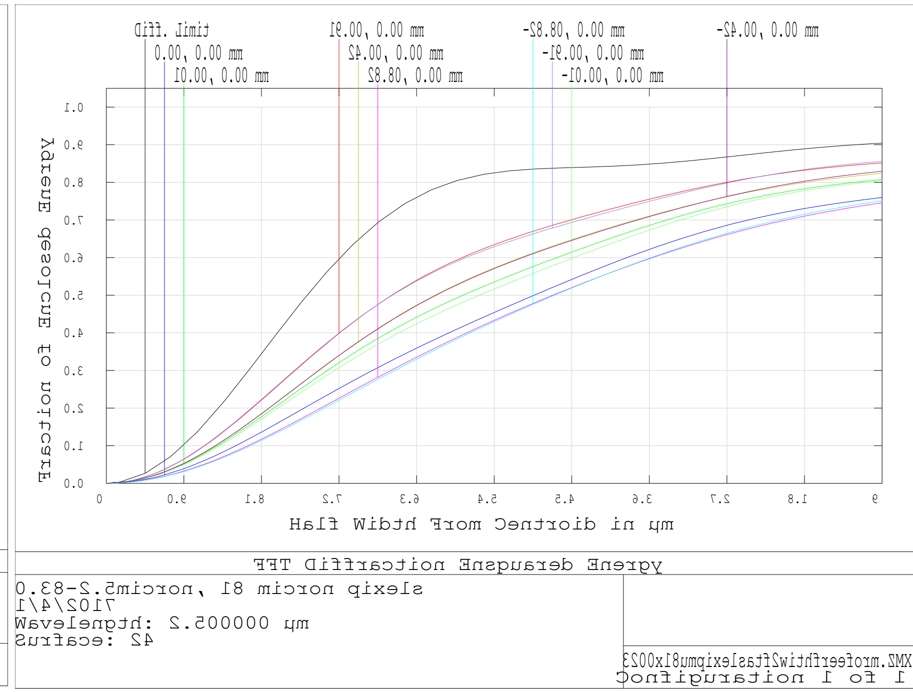
380 nm



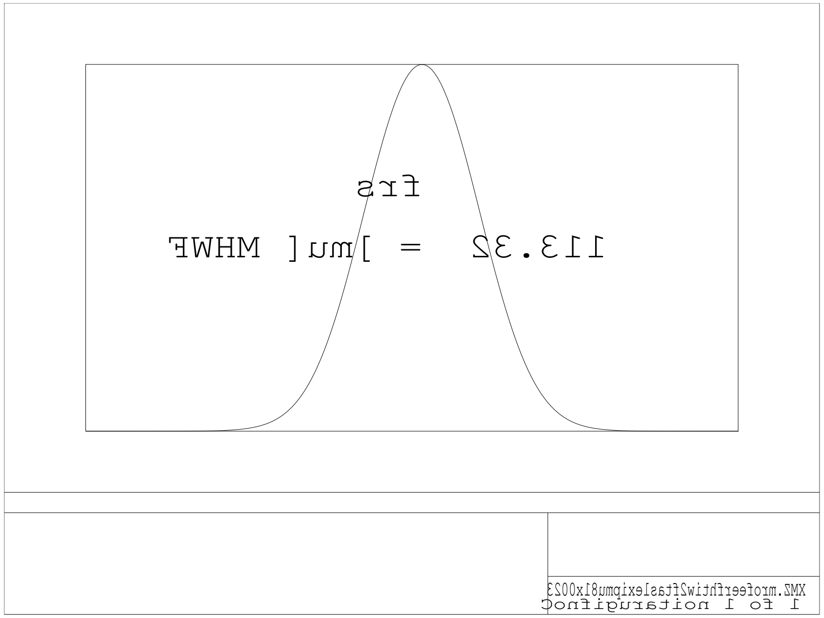
2500 nm

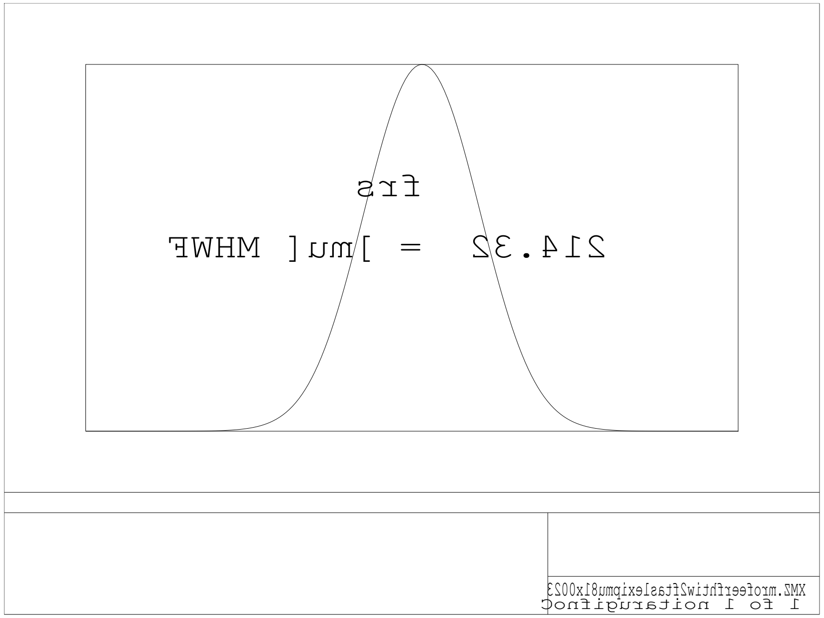
Over 74% of spot energy inside the pixel for all wavelengths



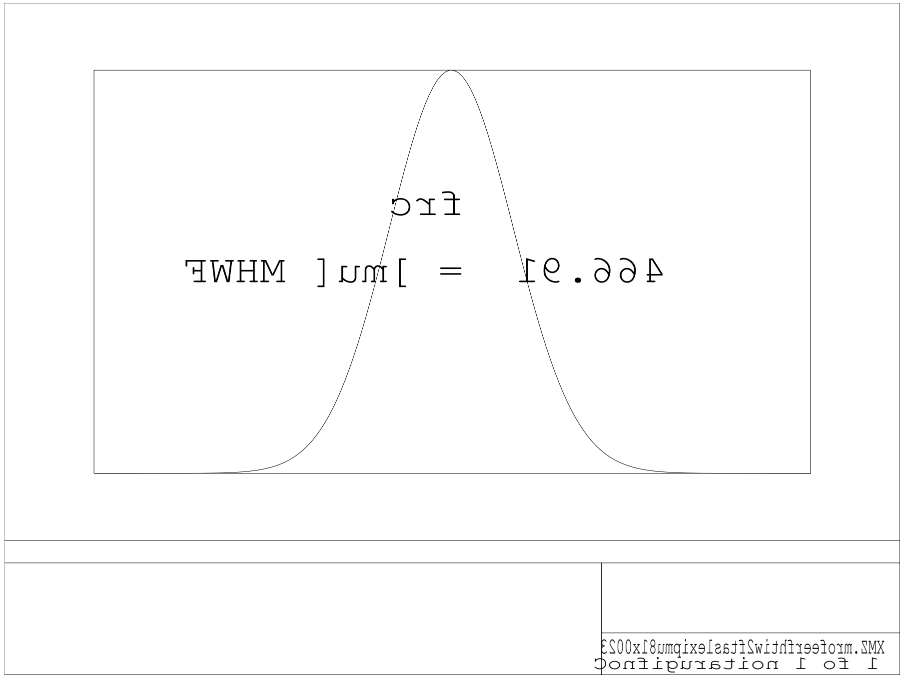


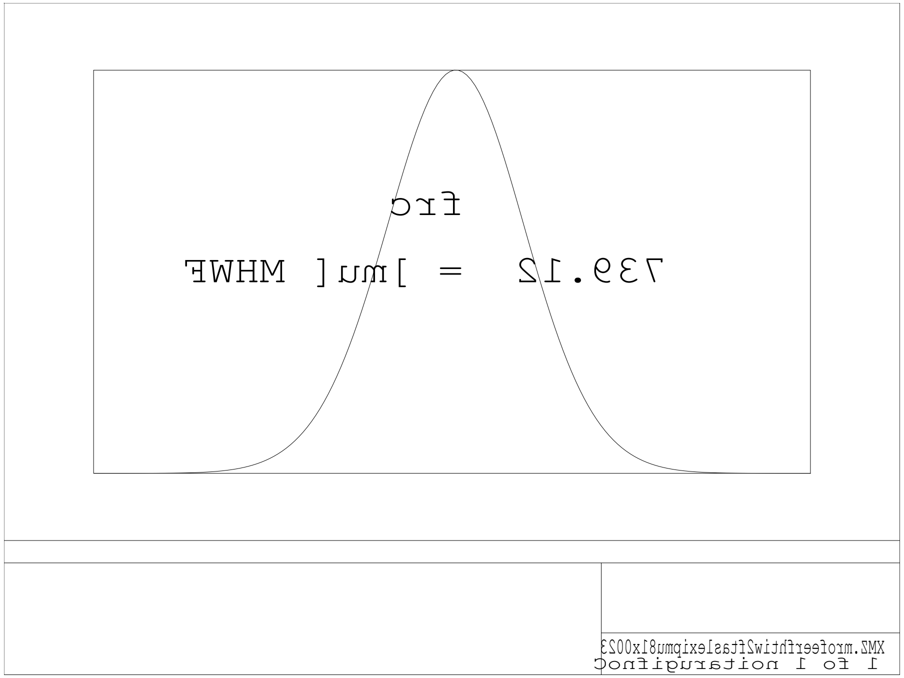
SRF variation through field is very small, example below for 1.2 µm. Max smile is 0.6 µm or 3.3%.



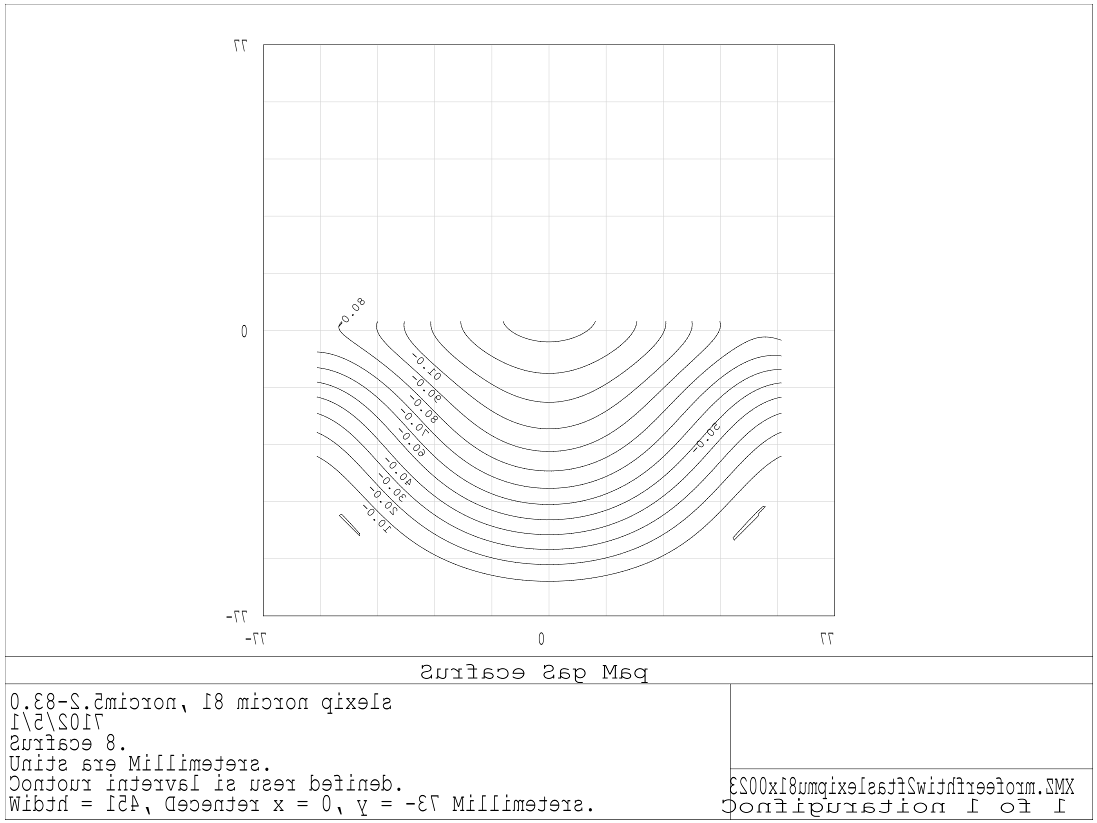


Maximum CRF FWHM variation through wavelength ~ 5.5%.
Keystone is negligible < 0.2 μm.





Contour plot of freeform surface with spherical term subtracted. Contour interval is 10 μm.



Conclusions

Utilizing the potential of imaging spectroscopy requires uncommon performance levels to be extracted from the instrument

Concentric imaging spectrometer forms have been advanced to very high levels of performance and are serving a wide range of applications

Design principles for telescope and spectrometer have been described and design/instrument examples based on these principles have been provided

Freeform optics can provide some theoretical advantages, remain to be proven in practice for these applications

ACKNOWLEDGMENTS

Overall leadership in Imaging Spectroscopy: *Robert O. Green*

Grating development: *Daniel W. Wilson*

System/concept development: *Michael Eastwood, Byron Van Gorp*

Data reduction and algorithms: *David Thompson, Byron Van Gorp*

Component and subsystems: *Rich Muller, Victor White, Karl Yee, Holly Bender, Bill Johnson, Justin Haag, Lori Moore*

Detectors: *Teledyne*

Instrument teams: *Sarah Lundeen, Scott Nolte, Ian McCubbin, Justin Haag, Mark Helmlinger, Chuck Sarture, Bill Johnson*

Science Collaboration: *Diana Blaney, Heidi Dierssen, Bethany Ehlmann, Simon Hook, Joe Boardman, Michelle Gierach*